A PROCESS DEVELOPMENT STUDY

# DESIGNING SPACE ACCESS SYSTEMS

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SYNTHESIS METHODOLOGY FOR CONCEPTUAL DESIGN OF FUTURE SPACE ACCESS SYSTEMS

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# SPACE ACCESS SYSTEMS DESIGN

## *Synthesis Methodology Development for Conceptual Design of Future Space Access Systems*

August 2017

This dissertation is submitted in partial fulfillment of
the Requirements for the Degree of
DOCTOR OF PHILOSOPHY OF AEROSPACE ENGINEERING
to the
Faculty of the Graduate School of
THE UNIVERSITY OF TEXAS AT ARLINGTON

# SPACE ACCESS SYSTEMS DESIGN

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# ACKNOWLEDGMENTS

Words are useless when it comes to thanking your creator, but I would still take this formal opportunity to first and foremost acknowledge Nisha Rana. I have known no greater human being, and understood the meaning of selfless, unconditional love by only being your son. And of course, the same goes for Satish Rana, my dad, the enabler and provider for this amazing life I am so grateful to experience. Thank you Sir for all your support and trust in my crazy dreams. Next, I would like to acknowledge my younger sister, Shikha Rana, who is already a better person than me, I bless you with my heart and soul. You are awesome. Also endless thank yous to my all extended family members and relatives who have loved me and showed me the value to strive for others, special mention, the 'Noble' Atesh Rana.

For the last five years, I have had the pleasure and honor of working alongside some of the smartest and most sincere people at the AVD Laboratory. A very sincere Thank You to first Dr. Amit Oza, Dr. Amen Omoragbon, and Dr. Lex Gonzalez for being the inspiring engineer figures. I learned a great deal of aerospace from the 2 AM discussions with you guys. Next, I would like to thank Dr. Mark Doug Coley. You, my dear friend, represent to me all that is genuinely good about Texas. I am glad to have had the chance to learn the meaning of aerospace engineering alongside a gentleman like you at the AVD. Further acknowledgments and gratitude to Dr. Eric Haney, Dr. Xiao Peng, Vincent Rickets and other past members of the AVD lab with whom I have had the privilege to share my work space and ideas. You have all contributed to this dissertation in some manner that I cannot directly quantify.

A very special Thank you goes to my dear friends and current AVD colleagues Thomas McCall and James Haley. They both contributed in this research directly as part of the conference publications that will follow soon based on the work presented here. With the help of both these fine gentlemen, I have been able to take on this huge research task and develop some meaningful and practical conclusions. The enormous amount of data generated during this research would not have been possible without their cooperation. Also, Thank you to David Woodward and Ian Maynard for the valuable reviews.

Finally, the most important person I would like to thank is my research supervisor, Dr. Bernd Chudoba. Thank you Sir, for EVERY-

THING. I would not be the person and researcher I am today, had you not given me the opportunity to join the elite group at the AVD. You gave me a chance without any prior conditions, when I was a novice in aerospace and guided me all along, stood by me in all the difficult times and supported me in ideas, resources and motivation. I have come to develop a attitude of respect for my work by only copying you all these years. There are no further adjectives that I can think of, to express my gratitude for you sir. So I humbly would just end with a greeting in my language, *"PRANAAM"*[1]

---

[1] *pranaam;*
- a respectful greeting made by putting one's palms together and often touching the feet of the person greeted,
- the act of paying obeisance' to a person, deity or entity.

# ABSTRACT

The early Conceptual Design (CD) of a Space Access System (SAS) is the most abstract, innovative, and technologically challenging phase throughout the entire aerospace product development life-cycle. While it is the most important life-cycle phase which influences around 80 percent of the overall life-cycle-cost, it is also the least understood design phase. The history of space access vehicle design provides numerous examples of projects that failed due to lack of a proper technology-hardware-mission assessment in the CD phase. The present dissertation addresses this crucial phase and develops a prototype best practice solution process to advance the current state of the art of the CD oriented vehicle design synthesis systems. The solution is a generic process that can be applied to all categories of the SAS. The Vertical-Takeoff Horizontal-Landing type SAS is selected as the demonstration case-study for the solution process. The research provides a proof of concept for how the proposed prototype solution process expands the scope and application of current applications of the CD assessment vertically across the SAS system‘s hierarchy and horizontally across the life-cycle phases of the SAS.

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# NOMENCLATURE

**Abbreviations**

| | |
|---|---|
| AHP | Analytic Hierarchy Process |
| AVD | Aerospace Vehicle Design Laboratory |
| BB | Blended Body |
| CD | Conceptual Design |
| CER | Cost estimating relationship |
| DB | Data Base |
| DBMS | Data Base Management System |
| DD | Detailed Design |
| GDSP | Generic Design Synthesis Process |
| KB | Knowledge Base |
| LB | Lifting Body |
| LEO | Low Earth Orbit |
| LRV | Lifting Reentry Vehicle |
| LV | Launch Vehicle |
| MDA | Multi-Disciplinary Analysis |
| PD | Preliminary Design |
| PP | Parametric Process |
| RFP | Request for Proposal |
| RV | Reentry Vehicle |
| SAS | Space Access System |
| SAS-GDSP | Space Access System-Generic Design Synthesis Process |
| SAV | Space Access Vehicle |
| SDP | System Development Process |

| | |
|---|---|
| SM | System Module |
| SPG | Space Planners Guide |
| SSTO | Single Stage To Orbit |
| STS | Space Transportation System aka The US Space Shuttle |
| TSTO | Two Stage To Orbit |
| VTHL | Vertical Takeoff Horizontal Landing |
| WB | Wing Body |

**Variables**

| | |
|---|---|
| $f_0$ | *TransCost* systems engineering and integration factor |
| $f_1$ | *TransCost* technical development standard correlation factor |
| $f_2$ | *TransCost* technical quality correlation factor |
| $f_3$ | *TransCost* team experience factor |
| $f_4$ | *TransCost* cost reduction factor from Learning factor |
| $f_6$ | *TransCost* cost growth factor for schedule deviation |
| $f_7$ | *TransCost* parallel organization factor |
| $f_8$ | *TransCost* country productivity factor |
| $f_{10}$ | *TransCost* technology progress cost reduction factor |
| $f_{11}$ | *TransCost* commercial cost reduction factor |
| $Alt_e$ | reentry altitude |
| $g$ | Earth's gravitational constant |
| $h$ | altitude |
| $I_{sp}$ | Specific impulse |
| $L/D$ | Lift-to-drag ratio |
| $r_s$ | orbital altitude of the circular satellite |
| $r_o$ | local radius of curvature |
| $V_1$ | velocity after deorbit maneuver |
| $V_e$ | reentry velocity |
| $V_{eq}$ | velocity during equilibrium glide phase |

| | |
|---|---|
| $V_i$ | instantaneous deorbit velocity decrement |
| $V_s$ | orbital velocity of the circular satellite |

**Greek letters**

| | |
|---|---|
| $\beta$ | ballistic coefficient |
| $\eta$ | lift loading coefficient or vehicle parameter |
| $\gamma_e$ | reentry flight path angle |
| $\gamma_1$ | flight path angle after deorbit maneuver |
| $\rho$ | atmospheric density |
| $\sigma$ | bank angle |
| $\tau$ | Küchemann‘s slenderness parameter |

*Chapter 1*

# INTRODUCTION & OBJECTIVES

> *"Once you make it to Low Earth orbit, you are halfway to anywhere."* [1]

Prospects for the space industry look brightest now in the form of a second revolution, a private one, that is based on profit and commercial success. Recent developments in the space community are seen all around the planet, as national space agencies and private companies are working on plans to establish a long-term human presence on the Moon and Mars. Amid this excitement of reaching to other heavenly bodies, we easily tend to forget that all those "Highways To Space" lead through the Low Earth Orbit (LEO) check point.

Developing a reusable, cheap, and regular LEO access capability is crucial to establish a sustained human presence in space. In this context, the biggest roadblock that the space industry has faced is the "cheap and reusable" part. In order to develop such a capability, it would then be a key requirement to parallel the flight frequency and operational easiness of the commercial airline industry.[2] In contrast, the space industry has not yet been able to develop a fully reusable airplane-like Single Stage To Orbit (SSTO) aerospaceplane. Consequently, the traditional Space Access System (SAS) has evolved as a complex system of systems, made up of multiple Space Access Vehicles (SAV), usually, a Launch Vehicle (LV) and a Reentry Vehicle (RV). The traditional LVs have been the expandable rockets that are used once for a mission and the majority RVs have been the ballistic type bi-conical capsules that perform a soft landing at a pre-selected site. Both designs are cost and operations inefficient. This scenario emerges as a bottleneck in the growth of the industry.

Particularly, the commercial space industry has shaped to be a non-mature industry demanding new paradigms and approaches in the conventional processes of designing and developing future generations of SAS. It then becomes necessary to examine the current state-of-the-art in the spacecraft design domain and develop required capabilities to meet the challenges faced in current times. This hypothesis is the baseline motivation for the current research study.

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[1] Robert A. Heinlein
One of the "Big Three" of science fiction authors along with Isaac Asimov, and Arthur C. Clarke. He is also known as "Dean of science fiction writers".

[2] *"If one can figure out how to effectively reuse rockets just like airplanes, the cost of access to space will be reduced by as much as a factor of a hundred. A fully reusable vehicle has never been done before. That really is the fundamental breakthrough needed to revolutionize access to space."*
- Elon Musk,
Founder, CEO, and CTO, SpaceX

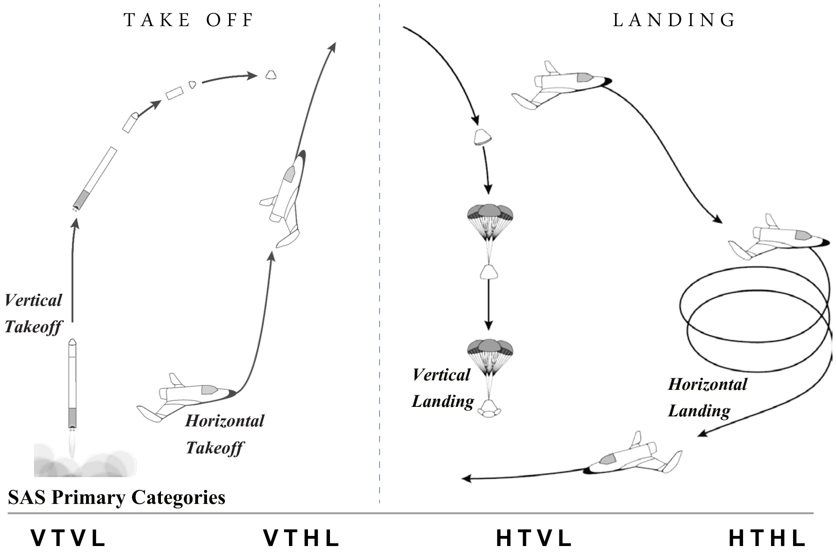

FIGURE 1.1 – Primary SAS Categories

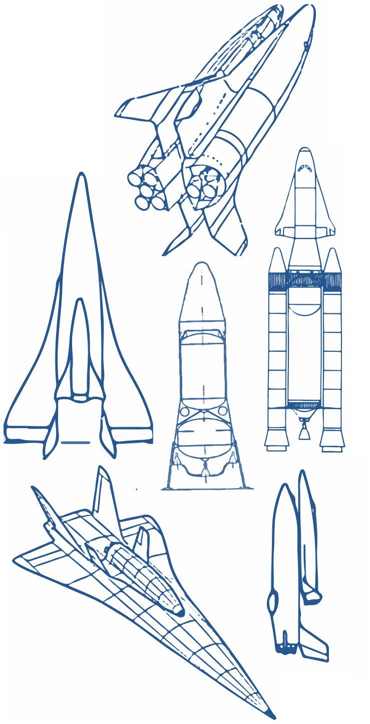

FIGURE 1.2 – Various SAS Configurations

## 1.1 *Space Access Systems - SAS*

### 1.1.1 *Background*

The Space Access System is the primary enabling requirement for the space industry. A SAS is composed of two primary elements; 1) a launch element, which is used to boost the payload to the orbit and, 2) a reentry element, the part that returns back to the surface. On this basis, four primary categories[3] can be defined as seen in Figure 1.1. Each of these categories can then have numerous variations depending on the specific mission of the vehicle. Further classifications of SAS are added depending on other factors like number of stages, payload capacity, et al. These factors are influenced by the configuration of the SAS, which in turn depends on the constituting SAVs (LV and RV). Since there are several types of launch vehicles and reentry vehicles, multiple SAS configurations are possible within each category. Most of these configurations have been conceptually studied by various organizations and industry alike. Figure 1.2 shows some distinct SAS configuration concepts. The history of space vehicle design is filled with numerous programs undertaken by leading space agencies and organizations all around the planet, aimed at developing a fully-reusable SAS[4]. Sadly, most of those programs were failed attempts costing billions of dollars of investment for the stakeholders. In-light-of these facts, it is necessary to consider why the path to reusability is that challenging? In order to realistically answer this question, it is necessary to first understand the SAS as a generic system.

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[3] HTHL: Horizontal Takeoff Horizontal Landing
HTVL: Horizontal Takeoff Vertical Landing
VTHL: Vertical Takeoff Horizontal Landing
VTVL: Vertical Takeoff Vertical Landing

[4] *Major canceled programs with the primary target to develop a fully reusable SAS:*

- Soviet - SPIRAL(1976), MAKS(1988).
- British - HOTOL(1982).
- USA - NASP X-30(1985), X-33 VentureStar(1994), DC-X(1991).

### 1.1.2 *Systems Perspective*

> “A system is an open set of complementary, interacting parts with properties, capabilities and behaviors emerging from the parts and from their interactions...The properties, capabilities, and behaviors of a system derive from its parts, from interactions between those parts, and from interactions with other systems...Altering the properties, capabilities, or behavior of any of the parts, or any of their interactions, affects other parts, the whole system, and interacting systems.“ [5]

In this capacity, Systems Engineering is a discipline that concentrates on the design and application of the whole(system) as distinct from the parts. It involves looking at a problem in its entirety, taking into account all the facets and all the variables.

SAS too, are complex systems that are comprised of several specialized parts assembled together to serve a common purpose. The system itself is greater than the sum of the constituent parts combined. The emergent properties inherent to the system are not associated to any one part, but instead, due to interactions between those sub-systems.

Thus, it becomes important to identify a hierarchy within the system to identify different levels of interactions among elements of the same class. An example of such a system hierarchy is the product hierarchy for STS shown in Figure 1.4 taken from NASA Systems Engineering Handbook[1]. This research adopts a more generic form of system hierarchy as defined by Hammond[2]. Table 1.1 lists the system's hierarchy consisting of six levels of hierarchy elements. The last column shows analogy for the SAS for every element category. The definition of constituent hierarchy elements establishes distinct vertical-levels of elements with reference to the overall systems level (SAS). It should be noted that in this hierarchy definition, a LV and a RV fall under the generic category of a SAV as both vehicles access the space environment (and hence are classified as Space Access Vehicle - SAV). Based on this hierarchy definition, the following characteristics are observed[6]:

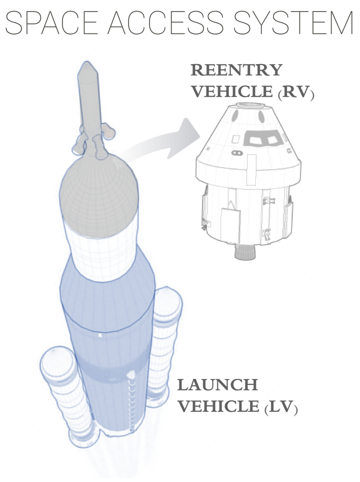

FIGURE 1.3 – SAS: Systems View

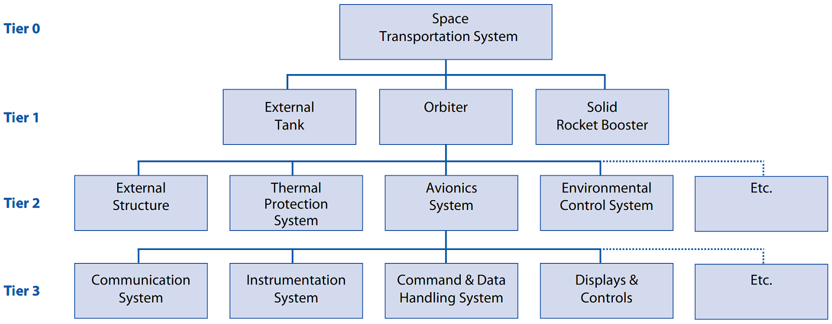

FIGURE 1.4 – STS product hierarchy from NASA Systems Engineering Handbook[1]

[5] Derek Hitchins
Advanced Systems Thinking.
Engineering, and Management,
Artech House, 2003.

[6] These characteristics are discussed in further detail in Sections 1.2.1 and 1.2.3

| Level | Element | Definition | SAS-Representatives |
|---|---|---|---|
| 1 | System | Set of interrelated entities working together as a whole to achieve a common purpose | SAS |
| 2 | Major Element | Grouping of closely ralated subsystems, often having a physical interface | SAV (LV, RV), External Tank |
| 3 | Subsystem | Functional grouping of components that perform a major function within a major element | Rocket motor, TPS et al |
| 4 | Component | Functional unit that may be viewed as an entity for purpose of analysis, manufacture, testing, and record keeping | Turbopump |
| 5 | Subassembly | Stockable unit consisting of two or more parts that may be disassembled for parts replacement | Printed Circuit Board(PCB) |
| 6 | Part | Single unit not normally subject to disassembly without destruction | Integrated circuit(IC) |

TABLE 1.1 – System hierarchy adopted from Hammond[2] and SAS Counterpart for each level.

1. Decisions regarding higher hierarchy levels have a greater impact on the overall system. For example, the decisions taken at hierarchy level-3 (Subsystem) for SAS pertains to selection of rocket motors (propulsion discipline) and would have a greater impact on overall SAS configuration as compared with decisions taken for hierarchy level-6 (Parts) which is the selection of integrated circuits etc.

2. Several elements of same hierarchy level integrate[7] together to form one element of the next level from bottom to top. Since there can be various combinations possible for elements at each level, trade studies are conducted to find the best-fit combination depending on mission requirements, see Figure 1.5.

3. Design occurs from top to down in the hierarchy, and hence impact of integration effects decrease with each hierarchy level. While designing a complex system like a SAS, integration at a higher hierarchy level is satisfied before establishing integration at the next lower level. The integration of LV and RV (both belong to hierarchy level 2) is crucial and important over the integration of several electrical components (belonging to hierarchy level 5).

4. Information quantity increases down the hierarchy chain as the system design progresses, while the information impact reduces. During initial design phases, information availability is restricted to higher hierarchy levels. During the early design phases, information available is limited to subsystems like propulsion, structures et al, while no information is available for the parts like integration circuits etc., nor is it required. As the design progresses into advanced design and fabrication phases, the detailed information is made available for specific parts but it has a negligible impact on the overall design of the SAS at this point.

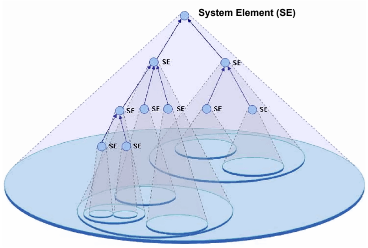

FIGURE 1.5 – System Element composed of lower-level System Elements[3]

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[7] Integration implies that the elements of same same hierarchy level are physically and operationally compatible with each other.

These primary tenets of system hierarchy play crucial role in the design and development process of SAS as discussed in the following section.

## 1.2 *Domain Specification*

This section establishes the research application domain and selects the SAS-type domain as the reference case-study in the first two subsections. The last sub-section addresses the scope of the problem.

### 1.2.1 *Application Domain - Conceptual Design Phase*

A technological product is developed to fulfill a specific purpose which defines its physical and operational characteristics. Likewise, a SAS is developed to provide transportation capability in the extremely harsh environment of space. This represent the primary requirement of the SAS design, which then leads to further detailed mission-specific requirements defined on the needs of the customer.[8] These requirements are inherently tied to the design process of the SAS as shown in following discussion.

» *Acquisition and Product Development:* The traditional landscape of the space industry has been such that the government agencies (NASA, USAF, ESA, etc) have been the primary operator whereas the role of commercial organizations (Lockheed, Boeing etc) have been limited to design, development, and manufacturing of SAS in general. The process followed by a government agency to acquire a SAS from a commercial entity is termed as the acquisition process. Tom Benson of the NASA Glenn Research Center provides a simplified diagram outlining the typical acquisition process prevalent in aerospace industry[5], see Figure 1.6. Benson states, *"The user has some need for an aircraft and a mission that the aircraft is to perform. The needs are determined by the user and the user defines his needs in a Request for Proposal (RFP). The RFP is a document that spells out what the aircraft must do. The user publishes this document and the various suppliers must make a determination if they can design an aircraft which meets the needs of the user....the supplier proposes a new design to the user based on results from the research groups."*

It must be noted here that acquisition process is outlined from the user's[9] perspective and is important to understand as it is inherently connected with the product development process. The acquisition process in the space industry is visualized in Figure 1.7 based on a hypothetical scenario where NASA as customer releases a RFP demanding a new launch platform. Major competitors from industry like ULA, BlueOrigin, SpaceX etc submit their individual designs to-

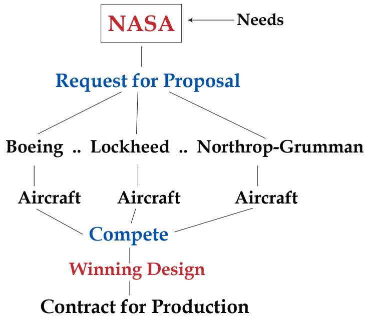


FIGURE 1.6 – Acquisition Process in Aerospace, by Benson[5]

[8] *"The mission objectives are imposed on the system by the customer, or user of the data. They are statements of the aims of the mission, are qualitative in nature and should be general enough to remain virtually unchanged during the design process. It is these fundamental objectives that must be fulfilled as the design evolves."*
*- Peter Fortescue(Spacecraft Systems Engineering)[4]*

[9] user is the stakeholder acquiring a service or a product

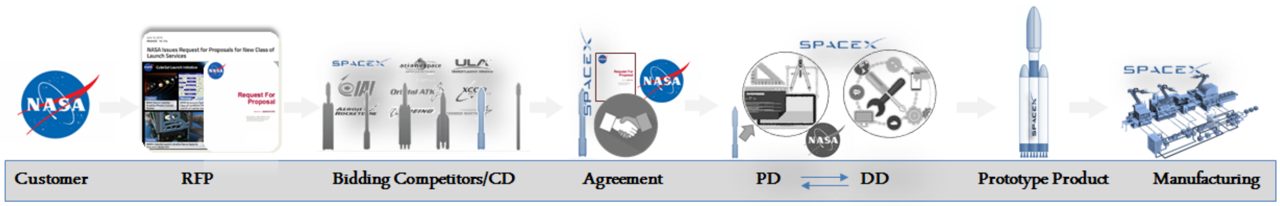


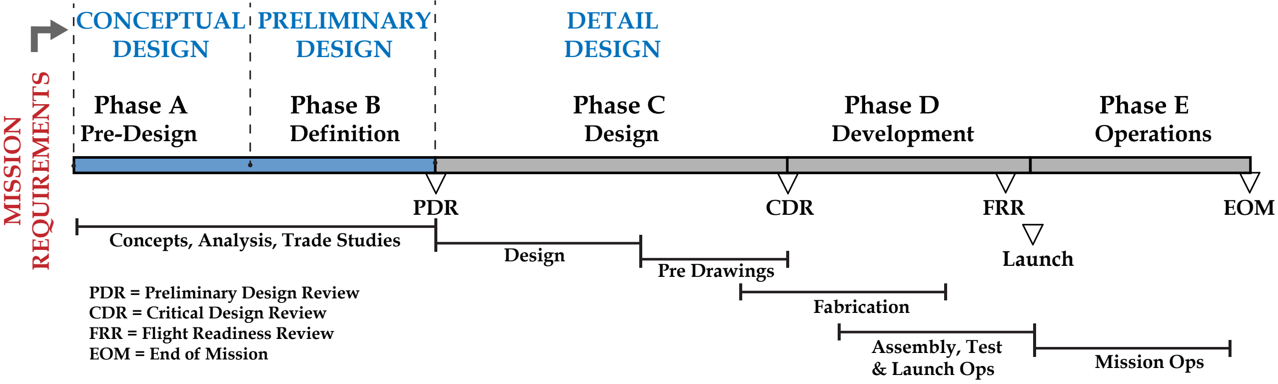
FIGURE 1.7 – General acquisition process in space industry

wards the RFP where SpaceX wins the contract and signs agreement to develop the product demanded by NASA. In this scenario, the first design concepts of the product is done in-house at the competing organizations. This first step in the product development process is the gestation phase of the design concepts and is referred as Phase-A or Conceptual Design.

The generic view of life cycle of a spacecraft project identifying major chronological phases is shown in Figure 1.8. The mission requirements are the first sets of inputs feeding directly to the Conceptual Design(CD), followed by Preliminary Design(PD) and Detailed Design(DD) phases. **The conceptual design phase is selected as the application domain for this dissertation because it has the greatest impact on the end product**, as explained next.

» *Role of CD phase in SAS Development Process:* Mission objectives are primary requirements and constraints defined by the user or customer in the RFP for a vehicle. In other words, the objectives are fundamental demands for the vehicle and are defined before a vehicle exists to meet those demands. The design of any product begins with these non-tangible demands as the first set of inputs. The conceptual design phase is the first step in the design cycle where a physical, tangible system is defined in response to non-tangible demands for

FIGURE 1.8 – Spacecraft Life Cycle. Modified from Brown[6]



the product. This abstract task of developing a physical, tangible system concept from non-tangible requirements is usually addressed by the advanced design team of the competing organizations [10]. Since, the first concept definition occurs in-house of every competing organizations, the details of the processes applied by the advanced design teams are company proprietary trade-secrets and are rarely available in the public domain[11].

The system design concepts defined at the CD phase must fulfill the following basic conditions before being further investigated and refined in PD and DD:

- Physically and technologically feasible system,
- Meets primary mission objectives,
- Successful business case solution.

Since a SAS is a system combination of vehicle configuration and hardware technologies, there can be multiple concepts that can effectively meet these three requirements. The goal of the CD phase is to assess the various combinations of vehicle hardware configuration and technologies for the given mission objectives. The design concepts that satisfy the technical and business case feasibility are then evaluated further in PD and DD phases, see Figure 1.9. A design specialist must be able to forecast the impact and benefits of new technologies in an integrated holistic vehicle system environment during this early design phase.

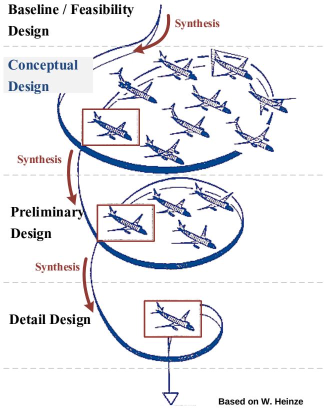


FIGURE 1.9 – CD phase assesses multiple vehicle concepts to identify optimum mission-configuration-technology combination. Reproduced from Heinze[8]

The CD phase assessment requires screening through a number of design concepts rapidly to identify the best mission-configuration-technology combination for the given requirements. This insight and information is of critical value during the conceptual design phase where the chief decision maker needs to be most informed about the potential advantages and risks within the available solution space, thus it does enable him to choose the best design concept to be further investigated. Mismatching technology requirements to the technology available (industry capability) leads to significant cost and schedule overruns. Failure to forecast those interrelationships is a problem during the early design phase, which is a primary reason why many past space access projects have been canceled over the years. The brief history of space access since the launch of the space age in 1957 contains numerous failed programs which could have been avoided with better-quality planning during the initial product gestation phase, overall leading to correct decisions during the early conceptual design phase.

» *Significance and Characteristics of CD:* It is no surprise that the early conceptual design of a space launch system is considered the

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[10] see acquisition process in Figure 1.7

[11] *"Design synthesis systems are the heart of aerospace vehicle design organizations (Boeing, Lockheed Martin, Airbus, etc). The development of a synthesis system is a demanding task and requires large research activities."*
*- Huang[7]*

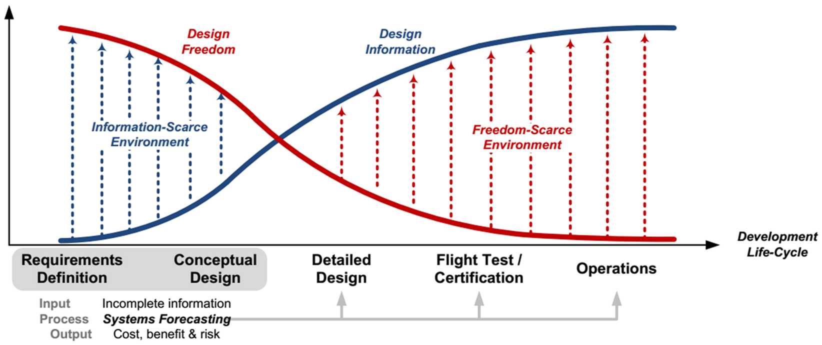

FIGURE 1.10 – Design Freedom vs Knowledge available. Reproduced from Haney[10]

most abstract, innovative, and technologically challenging phase throughout the entire aerospace product development life-cycle. Chudoba notes, *"the general life-cycle characteristics are established first during the conceptual design (CD) phase, clearly before a design proposal can be released to the follow-on design phases such as preliminary design (PD), detail design (DD), flight test (FT), and finally operation and disposal. CD is one of the most crucial life-cycle stages for a space program as the majority of the important decisions are locked down during this very development phase. As a rule of thumb, it can be assumed that around 80% of the flight vehicle configuration and mission tandem are determined during the CD phase alone, which is the key phase where the initial brainstorming has to take place."*[9] It is the design decision-making during the CD phase that defines the mission-configuration-technology combination towards either a successfully implemented product responding to a correctly determined profitable business case or a failure with potentially detrimental results.

Since the vehicle does not yet exist at the beginning of the CD phase, minimum design data/knowledge is available whilst the freedom to change the design is maximum for the very same reason. Consequently the cost to make a design change at this stage is minimum as the design-configuration is not yet locked and the changes made are still cheap during the simulation phase. Figure 1.10 shows the information-scarce and maximum design-freedom aspects of CD phase. As the development process moves into the PD and DD phases, the design freedom reduces as each decision taken restricts the overall design freedom. At the same time, the knowledge about the product increases as more specific and detailed decisions are made. This aspect is first discussed in observations made regarding the tenets of the system hierarchy definition, leading to the conclusion that a system is designed from top-down in hierarchy level. An alternate interpretation of this feature is that as the design moves from CD to DD, more information is made available for the lower hierarchy elements, but since the design freedom is now significantly reduced (as the design is locked), this information has the least effect on the overall system design.[12].

An important characteristic trait of CD (owing to the information-scarce environment) is that at this stage only the primary design drivers are considered that have the maximum influence on the overall design. In context of the system hierarchy elements defined in Section 1.1.2 only the top three hierarchy levels are examined during the CD assessment, leading to overall systems feasibility establishment. As shown in Figure 1.11, the overall SAS design (hierarchy level-1) would be most affected by the choice of LV and RV elements (SAV at hierarchy level-2) which themselves are based on the combination of their constituting subsystems like the propulsion system and geometry shape selection etc (Subsystems at hierarchy level-3). This aspect is also addressed while discussing the tenets of the system hierarchy. Furthermore, since the CD phase does assess the technological feasibility of the design solution-space considering top hierarchy levels, the method of the assessment has to take into account the analyses of individual subsystems at hierarchy level-3 and their integration to give various options for elements at hierarchy level-2. The subsystem are representative of the classical aerospace disciplines like aerodynamics, stability and control, propulsion etc, while their integration into a SAV is mathematically established by multi-disciplinary design integration processes. The methodology to integrate the disciplinary analysis (representing the subsystems of a SAV) in a mathematical framework is referred as a *synthesis framework*.[13]

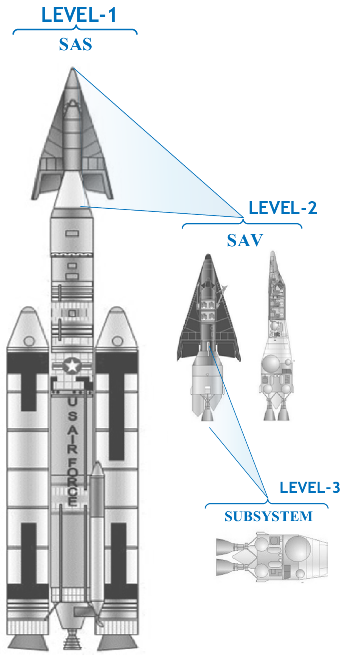

FIGURE 1.11 – Top three hierarchy levels of SAS constitute of the primary design drivers during the CD phase.

A key feature of the CD phase is that the integration process and disciplinary methods implemented during the CD are focused on the highest-of-important design variables. In other words, the primary concern during CD phase is to know what variable would result in the largest change in design. Hence, the emphasis during CD assessment is on the high-degree-of-correctness and multidisciplinary-integration rather than high-degree-of-accuracy and disciplinary-specific. To this effect, the use of high-fidelity disciplinary methods is not plausible for the CD phase, nor is it advised, as high-fidelity methods do require more information than what is typically known during the early CD phase. Then, the simpler analysis methods are preferred during the CD phase which take into account only the primary design drivers, require minimum input data, allow to measure the maximum change on system design, and can be iterated rapidly to produce a design solution space which is then assessed for mission-feasible concepts.[14]

Ironically, despite the critical nature of the CD phase, this early phase is less understood as compared to any of the later design phases. A primary reason for this trend is seen by observing the history and

[12] see Table 1.1 and related discussion of hierarchy levels in Section 1.1.2

[13] Synthesis methodology is addressed in detail in Section 2.3

[14] *Complexity of CD phase:*
A simple hypothetical scenario shows the complexity of a CD assessment level where if only primary five design disciplines are considered (geometry, aerodynamics, propulsion, trajectory and weights) and a first-order analysis method is used for each just calculating two most important parameters for each disciplines. Then, the integrating MDA framework is solving for ten variables, when practically no information is available for any discipline since the vehicle and its subsystems do not yet exist.

evolution of computing power along with growth of space industry. The discipline specific higher-fidelity tools require greater input data and thus demand higher computation capability (eg CFD analysis). With the advent of computers, as the computational power grew, it was applied primarily towards developing higher accuracy disciplinary toolsets ignoring the overall system integration mindset of the multi-disciplinary sciences. Amit Oza[11] demonstrates in Figure 1.12 how the evolution of disciplinary-specific toolsets from the 1970s gained preference with increased computation capability as the system integration capability was neglected.

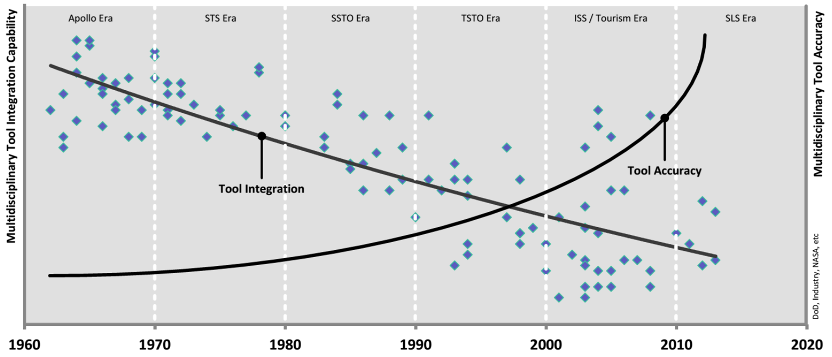

FIGURE 1.12 – Product Development Tool Multidisciplinary Data Integration and Accuracy. Reproduced from Oza[11]

Given the significance of the CD phase in SAS development, it is thus critical to improve the current state of the art of capability implemented for this gestation design phase. This research study does focus on advancing the CD capability as applicable for the design of the future generations of SAS. Figure 1.13 provides a visual summary of characteristics, significance and current standing of the CD phase and its interaction with SAS system hierarchy elements.

### 1.2.2 *SAS Domain: TSTO-VTHL*

The four categories[15] of SAS defined in Section 1.1.1 considers only launch and reentry aspects of the system. The classification scheme can be further expanded when the number-of-stages attribute is also taken into account. For example, a VTHL category of SAS can have several design concepts options with different number and types of stages, and different modes of mission operations. Figure 1.14 shows various VTHL configurations studied in past projects. A typical space mission can be divided into three phases of operations, namely: take-off, mission-operation, landing. Specific combinations of these phases give a distinct SAS concept. One example of a SAS concept can be: vertical takeoff, two-stage to orbit, vertical landing system or a TSTO-VTVL (eg. Titan III with Gemini reentry vehicle). Similarly, another

[15] HTHL: Horizontal Takeoff Horizontal Landing
HTVL: Horizontal Takeoff Vertical Landing
VTHL: Vertical Takeoff Horizontal Landing
VTVL: Vertical Takeoff Vertical Landing

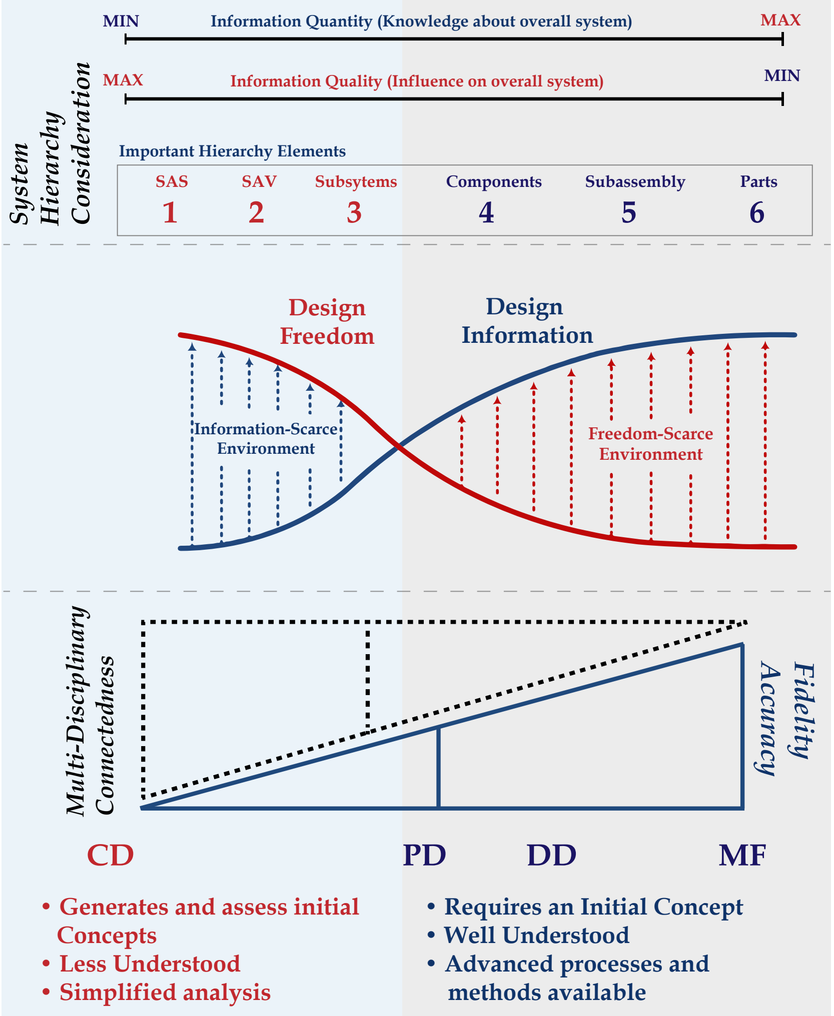

FIGURE 1.13 – Conceptual design characteristics and significance for SAS system hierarchy elements.

example can be a vertical take-off, two-stage, point-to-point, horizontal landing system TS-PTP-VTHL (eg. DLR SL7). A SSTO-HTHL system would then represent the ideal, fully reusable aerospace plane type SAS configuration that still remains elusive.

The horizontal launch capability is desirable to furnish the airplane's easiness to board the spacecraft and takeoff from a runway. Several programs[16] in the past have tried to use a horizontal takeoff first stage launch vehicle, but no operational vehicle was developed. This capability is difficult to achieve (limited by the technology) as the state of art propulsion systems are not sufficient to provide the energy required to escape the Earth's gravity-well.

In lack of the horizontal launch options, vertical takeoff rocket boosters have been the primary means to access space. Traditional vertical launch rocket systems are expandable multi-stage systems which are

[16] RTTOCV and ILRV program concepts (1960s,USA), Junkers RT-8 (1960s, Germany), SPIRAL program (1960s, USSR), ALSV concepts (1970s,USA), TAV concepts (1980s, USA), Sanger-II (a980s, Germany), ESA FESTIP concepts (1990s Europe), ORYOL concepts (1990s, Russia)[12]

discarded after a single use, leading to the high costs of space access. Several past programs [17] unsuccessfully tried to develop reusable vertical takeoff launch vehicles, but it wasn't until recently that the commercial company like SpaceX has been able to successfully reuse just the first stage of a vertical launch rocket booster. Even though this represents only partial system reusability, SpaceX has shown it to be an economically successful option by providing launch services at significant lower prices compared to the established industry players[13]. Additionally, Livingston[14], Andrews et al[15] and Diessel et al[16] in the past studies provide comparative assessments of horizontal and vertical launch modes showing that the vertical launch mode is the preferred mode considering near-term launch capability. Dissel concludes,"if a near-term launch capability is desired, the fully reusable TSTO rockets are close competitors with the airbreathing vehicles and are the next logical improvement over current rocket launch systems."[16]

When discussing the reentry segment of the SAV, traditional method has been to use a ballistic steep reentry vehicle such as Gemini, Mercury, Apollo etc. These vehicles are the first generation of reentry designs with very low performance capability, essentially falling back to the surface and using parachutes to execute a landing on water or land. As a result, ballistic reentry vehicles experience very high heat-flux and reentry loads and require a heavy ablative heat shield for their thermal protection system. Due to a low hypersonic lift-to-drag ratio, the capsule has a very small landing footprint, which severely restricts the deorbit window and in-space mission capability. Despite the low performance and limited mission capability, the ballistic vehicle still represents a simpler design that is easier to manufacture and integrate with the traditional launch vehicles.

On the other hand, horizontal landing SAVs offer considerable mission, operations and cost advantages over the ballistic counterpart.

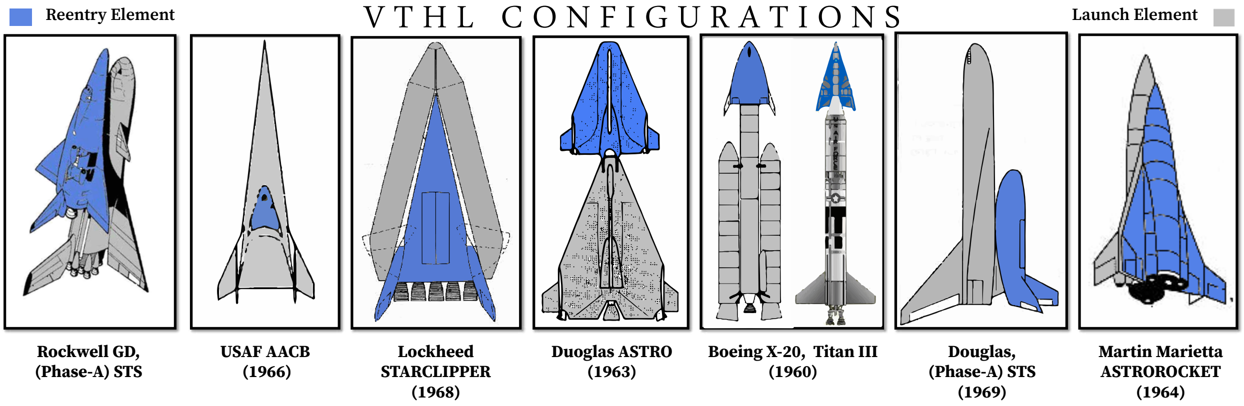

FIGURE 1.14 – Examples of VTHL type SAS designs explored under historical programs

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[17] Phillip Bono's OOST and ROMBUS (1960s concepts), Kraft Ehricke's NEXUS (1960s concept), McDonnel Douglas's DC-X (1991-1993), Lockheed Martin's VentureStar (1995-2001)[12]

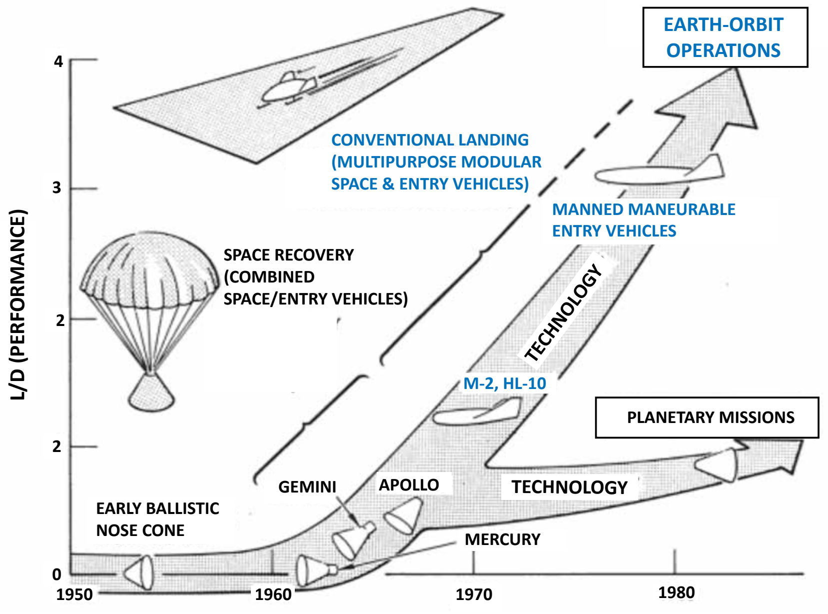

FIGURE 1.15 – LRV vehicles were identified from the beginning as the most suitable options for the Earth-Orbit operations as forecasted in this image from the early 1970s. Reproduced from Loh[17]

Sänger & Bredt[18], Tsien, Dornberger, Ehricke[19], Eggers, Allen & Neice[20] published the fundamental assessments during the 1950s, addressing hypersonic Lifting Reentry Vehicle (LRV) performance overall, demonstrating the conceptual feasibility. Parametric studies by Eugene Love[21],[22],[23],[24] further emphasize the advantages of lifting reentry over ballistic vehicles specially for Earth-orbit based missions, see Figure 1.15. Following these seminal studies, space organizations around the world have initiated numerous programs to develop a SAS employing lifting reentry[18]. Since then, a vast amount of research and development has been dedicated towards understanding the design and operational requirements of LRVs resulting in operational vehicles like STS, Buran and X-37. Currently, several organizations and private companies are actively pursuing LRV designs and have currently projects targeted to accomplish a fully reusable reentry vehicle stage. Summarizing the above discussion, following conclusions can be drawn regarding the current SAS scenario:

- SSTO-SAS are not feasible with the current state of technology. Lessons from the past projects show that this category require extensive R& D effort and a paradigm shift in several technologies.
- Horizontal launch systems share similar drawback to SSTO-SAS and are not the most economically feasible near-term solutions.
- Partially reusable vertical launch vehicles are currently under development at a tremendous growth rate, causing market disruption

[18] Discussed in detail in Section 2.2.1

and may prove cost effective. These systems are on a faster trajectory to achieve full system reusability than developing a SSTO launch system.

- Ballistic reentry vehicles are simpler to design and manufacture but show restricted overall performance and limited mission operations capabilities.
- Lifting reentry vehicles are higher performance vehicles with a vast range of mission capabilities. These vehicles perform horizontal landing on a runway and are most suitable candidate for tourism and commercial market of the future. Additionally, LRVs have been study extensively in the past and are currently being investigated by space entities all over the globe.

Based on the above observations, **this dissertation adapts a TSTO-VTHL system[19] configuration as the SAS case-study to be investigated in the domain of CD phase application**. From this point onwards, the LV and RV are addressed in context of the VTHL class of SAS, unless specified otherwise.

### 1.2.3 *Scope and Hypothesis of the Dissertation*

The definition of the CD phase as the application domain helps to define the limits under which this dissertation would address the problem of the SAS design. The TSTO-VTHL SAS class is selected as the primary case-study to be used to develop the solution required. To facilitate a broader spectrum of discussion, the TSTO here refers to two individual elements of the SAS required to obtain the orbital altitude, namely, a launch element[20] and a lifting reentry vehicle[21], see Figure 1.16. Thus, the SAS itself can be equal to a two-stage vehicle where a single-stage rocket booster is used to boost the LRV to a parking orbit and the LRV then attains the orbital altitude by itself. Another scenario can be a SAS configuration where a traditional two-stage LV (eg. ULA Atlas-V) is used to boost a LRV to orbital altitude, making the SAS a three stage vehicle. The relation between total number of SAS stages and the LV stages is given by, $SAS_{TotalStages} = LV_{Stages} + 1$

A multi-disciplinary framework or a synthesis methodology is the primary toolset used in the CD phase to derive the conceptual feasibility and generate a solution space of potential design concepts for the specific mission requirements. The disciplines represent primary subsystems that denote major functional characteristics of the vehicle. In the context of the system hierarchy defined for the SAS, the subsystems fall under the hierarchy level-3 and are integrated together using a synthesis methodology to form a SAV. A detailed discussion of historical and current state of art for the synthesis methodologies

[19] In the context of a complete SAS, a launch vehicle is considered as one element by itself and thus a TSTO system refer to the SAS which uses atleast two SAS elements, namely LV and RV to attain the orbit.

[20] The launch element here refers to a rocket powered launch vehicle which itself can be a single stage element or a conventional multi-stage launch vehicle.

[21] The LRV is a single entity that performs de-orbit burn and lands horizontally.

is presented in Section 2.3 addressing lessons learned from reviews of more than 156 past and present synthesis methodologies.

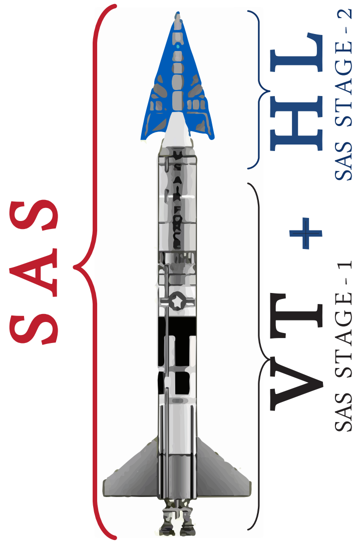

FIGURE 1.16 – TSTO-VTHL SAS: Top-Level systems definition.

It is seen that traditional synthesis methodologies are configuration oriented and address only a specific class of SAV. The primary reason being that each SAV operates in a different environment and under different constraint for a specific function and hence have different requirement for the constituting subsystems. The main function of a LV is to access the orbit from the ground and thus the propulsion system plays a crucial role in working against the Earth's gravity, moving in opposite direction to the gravity force. A LRV is used to return back to the ground from orbit and here the aerodynamic lift is the crucial function used to fight Earth's gravity while moving in the direction of the gravity force. Thus both vehicles are different in operational and technology requirements, but fall under the same class of SAVs and are integrated together as a SAS. Due to this difference, the traditional CD synthesis methodologies address only one specific SAV class, connecting hierarchy levels 2 and 3.

As further described in detail in Section 2.3, Chudoba[25] in 2001 conducted an exhaustive survey of the evolution of flight vehicle synthesis methodologies [22]. The survey identifies five generation of synthesis approaches where Class V denotes the future generation of generic design capability. Chudoba defines *"Class V Synthesis as a design process NOT a design tool; concluding that more emphasis should be placed on developing the capability of a synthesis system as opposed to the implementation of the tool itself."*[26] To this end, this dissertation aims to develop a Generic Design Synthesis Process (GDSP) that addresses a SAS as an integrated system where the constituent SAVs are parts

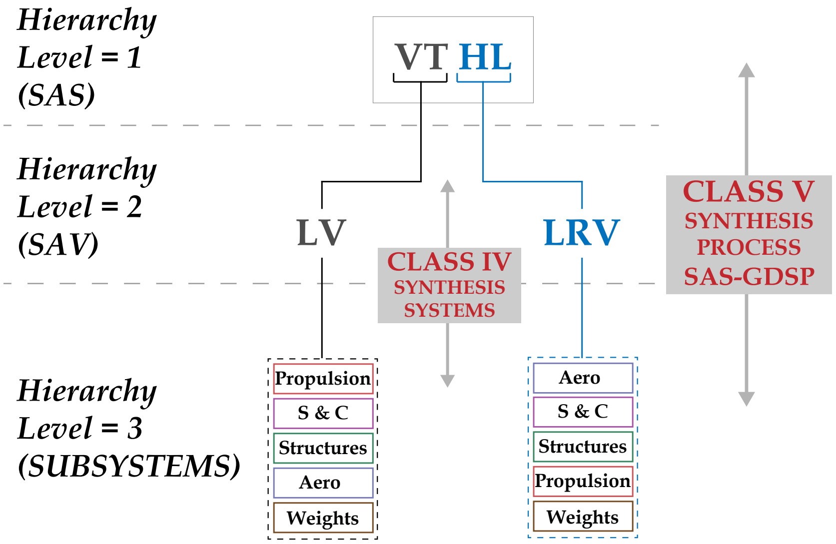

FIGURE 1.17 – SAS-GDPS expands the applicability of CD process vertically across hierarchy levels 1-3

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[22] The review addresses 115 synthesis methodologies covering the state of design synthesis approaches from past to then state of the art, circa 2001

of the whole system. This would be referred to as **SAS-GDSP** for convenience hereafter. It is important to note here that a methodology is distinctly different from a process as clarified by the following dictionary definitions:

> *methodology:*
> - a system of methods used in a particular area of study or activity.
> eg. "a methodology for investigating the concept of focal points"
> *process:*
> - a series of actions or steps taken in order to achieve a particular end.
> eg. "writing this dissertation was a long process"

The TSTO-VTHL SAS class is used as a case-study to develop and verify the SAS-GDSP but it could be applied to other SAS classes (HTHL, HTVL, VTVL) by following the same process but using the class-specific data, knowledge, and analysis methods. Existing Class IV synthesis approaches are applied for the synthesis of constituent SAVs at hierarchy level-2. In comparison, the SAS-GDSP can be executed at hierarchy level-2 (SAV) and/or at hierarchy level-1 (SAS) depending on the scope of the program, see Figure 1.17. Thus, Class IV synthesis approaches integrate hierarchy levels 2 and 3 whereas the Class V SAS-GDSP would be able to integrate hierarchy levels 1, 2 and 3. The range of the design options to assess by taking into account only the top-three hierarchy levels can be enormous as the number of options at a hierarchy level compound exponentially by trading elements at the next lower level. This effect is visualized in Figure 1.18 where the disciplinary trades at hierarchy level-3 give a unique SAV at level-2. The combination of LVs and LRVs then gives unique SAS options which form the overall solution space of feasible design concepts.

Limited by the time and manpower constraints, this research study would confine the application of SAS-GDSP for subsystems to only the LRV segment of the SAV at hierarchy level-2. Synthesis of disciplinary subsystems at level-3 in a multi-disciplinary kernel would be

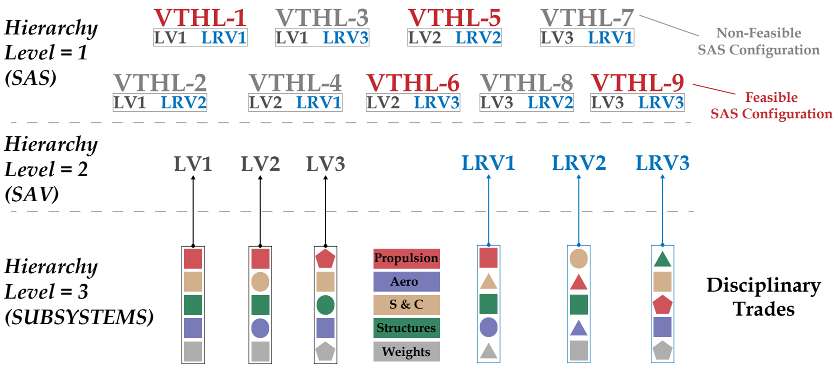

FIGURE 1.18 – Number of design options at a hierarchy level grow exponentially with the number of trades considered at the lower level.

considered for the LRV. The LV options are not synthesized through the subsystem synthesis like the LRV. Instead, the LVs are selected as various combinations of first and second stages, based on current available technology level. These two SAV components are integrated at the SAS level next, thus proving design capability of SAS-GDPS at the SAV level (for LRV segment) and at the topmost SAS hierarchy level. Once the technological and physical feasibility is established, the SAS level concepts are assessed for a successful business case feasibility using a cost-per-performance analysis. With these specifications, the next section describes the main research hypothesis that need to be fulfilled to prove the solution concept.

## 1.3 Research Outline

Chapter 2 next provides an extensive review of the literature for the VTHL case-study and the CD phase assessment capabilities and characteristics. This review has been an extensive effort that educated the author on the primary needs for the proposed solution.

Chapter 3 then provides a logical solution architecture of the solution describing what elements needs to be created and how to create them in order to develop a truly state-of-the-art synthesis capability.

Chapter 4 implements the solution process and describes the physical architecture of the solution concept. It then shows the results of applying the solution process for hierarchy level-2 for sizing specific and generic LRV cases. More than 700 uniques design concepts have been sized and analyzed as an outcome of this chapter.

Chapter 5 implements the generic solution concept for the VTHL SAS at the hierarchy level-1 and shows the unique capability of the prototype solution process as truly generic in nature and expanding the scope of the CD phase assessment capabilities.

Chapter 6 discusses the original contributions that were produced from this dissertation.

Chapter 2

# LITERATURE REVIEW

> *The purpose of conducting a literature review is to understand your intellectual heritage, your intellectual genealogy. Anytime we undertake an inquiry into a particular issue, we are building on the knowledge of others, and we need to know what that knowledge is. It is part of our obligation as scholars to understand what work has come before us, what concepts, methods, and measures we've inherited.*[1]

This chapter provides a detailed account of the literature review conducted to support the research hypothesis presented in the Chapter 1 and to gain an in-depth understanding of the subject matter. The first section describes the methodology applied to carry out an organized literature review and the tools implemented to create a central source library. The second section addresses a comprehensive review of the case-study configuration, focusing mainly on lifting reentry vehicles. A primary motivation for this review has been to understand fundamental design aspects for the selected SAS case-study (TSTO-VTHL) and collection of information related to this SAS class and its constituent elements as available in the public domain. This survey does assess the VTHL configuration from the disciplinary and design integration perspective to identify the current CD practices and capabilities available for the selected SAS case-study.

The third section then focuses on the review of the design synthesis systems in order to understand the current best practice capabilities as applicable to the SAS case-study. Classical and modern design systems are addressed in this review to identify the primary requirements for the *Space Access System - Generic Design Synthesis Process (SAS-GDSP)*. The understanding gained from reviews in Sections 2.2 and 2.3 is applied to justify the research hypothesis outlined in Chapter-1 (Section 1.2.3) and it serves as the foundation to develop the specification for the SAS-GDSP solution concept. The specification outline the characteristic requirements and it represents the capability qualification that the SAS-GDSP should be equipped to perform.

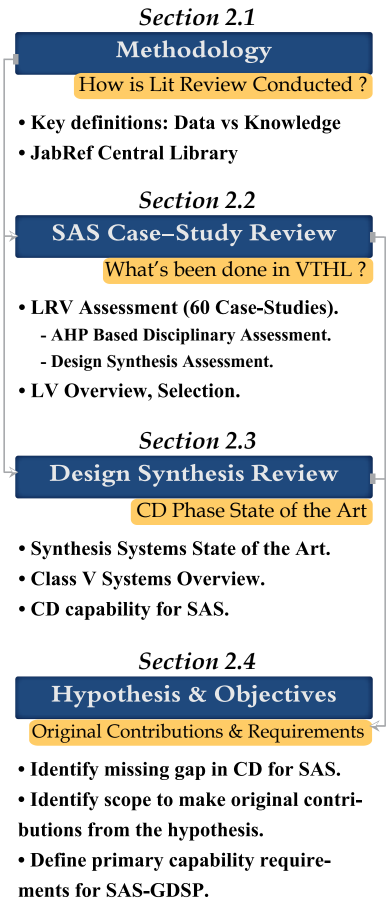

FIGURE 2.1 – Chapter-2 Overview

## 2.1 *Literature Review Process*

This section describes the process adapted to carry-out the literature review in a systematic manner, followed by the analytic description of

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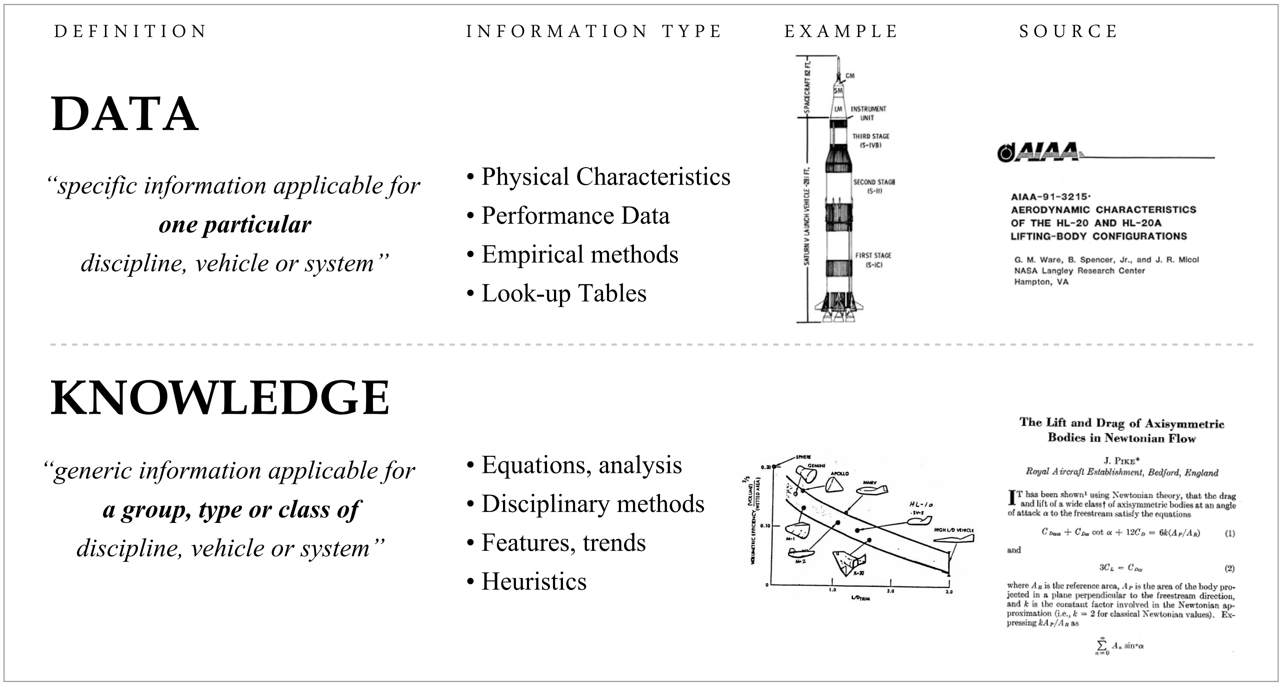
[1] Michael Quinn Patton,
Director, Utilization-Focused Evaluation
St, Paul, MN



DEFINITION | INFORMATION TYPE | EXAMPLE | SOURCE

**DATA**

*“specific information applicable for* ***one particular*** *discipline, vehicle or system”*

- Physical Characteristics
- Performance Data
- Empirical methods
- Look-up Tables

AIAA-91-3215
AERODYNAMIC CHARACTERISTICS
OF THE HL-20 AND HL-20A
LIFTING-BODY CONFIGURATIONS

G. M. Ware, B. Spencer, Jr., and J. R. Micol
NASA Langley Research Center
Hampton, VA

**KNOWLEDGE**

*“generic information applicable for* ***a group, type or class of*** *discipline, vehicle or system”*

- Equations, analysis
- Disciplinary methods
- Features, trends
- Heuristics

The Lift and Drag of Axisymmetric
Bodies in Newtonian Flow

J. Pike*
*Royal Aircraft Establishment, Bedford, England*

It has been shown[1] using Newtonian theory, that the drag and lift of a wide class† of axisymmetric bodies at an angle of attack $\alpha$ to the freestream satisfy the equations

$$C_{D\alpha\alpha} + C_{D\alpha} \cot \alpha + 12C_D = 6k(A_P/A_R) \qquad (1)$$

and

$$3C_L = C_{D\alpha} \qquad (2)$$

where $A_R$ is the reference area, $A_P$ is the area of the body projected in a plane perpendicular to the freestream direction, and $k$ is the constant factor involved in the Newtonian approximation (i.e., $k = 2$ for classical Newtonian values). Expressing $kA_P/A_R$ as

$$\sum_{n=0}^{\infty} A_n \sin^n\alpha$$

FIGURE 2.2 – Difference between data and knowledge, and their primary literature sources

literature review and applications.

### 2.1.1 Methodology

A thorough examination of data and information available in the public-domain has been conducted throughout this research. A systematic approach has been adopted to organize the data into practical and useful information. A consistent classification scheme has been developed for making the literature review practical for the author and therefore accessible to the next generation of researchers. For this purpose, following working definitions have been defined to clearly and distinctly identify the specific terminology.

- *Data:* Any piece of information that is specifically applicable to one specific discipline, vehicle or system.
  eg, $TOGW_{Saturn-V} = 6,540,000lb$
- *Knowledge:* Any information that is applicable to not just one case but applicable for a generic group, type or class of objects.
  eg, $L/D_{LRV} > L/D_{Ballistic-Capsule}$

These definitions are adopted and modified for the current research and act as only the working definitions. In the standard definitions of ‘Data’, ‘Information’ and ‘Knowledge’ (often abbreviated as DIK), data is considered as just the raw numbers and the lowest form while information is usually defined as data with context. This view of DIK is primarily derived from the IT industry, as for a machine the numbers have no meaning without context. In the current view of things, the author finds that numbers used in the current research have inherent context of the aerospace domain. Following this logic, the terms 'Data' and 'Knowledge' are considered as different forms of 'Information' where a simple number like L/D = 2.1 have a lot of inherent information. In this context, information is used as an attribute to 'Data' and 'Knowledge'.

An example of data would be the information like gross take off weight of Saturn V launch vehicle being 6.5 million lbs. Here, the information available is specifically applicable to one launch vehicle. On other hand, example of knowledge as defined above would be a statement like, lifting reentry spacecraft have high lift-to-drag ratio than a reentry capsule. Similarly, an analytic equation would be knowledge-type of information as it can be applied for any number of generic cases while the output of an analytical equation for a particular case would be the data. This distinct definition of knowledge and data is then applied to specify literature sources containing the respective information. The concept is shown in Figure 2.2.

Classification of literature sources as data or knowledge-based sources does provide a structure to organize and manage a central library which is of special relevance to a design engineer. As mentioned in the previous chapter, the CD phase tends to be weak on the knowledge available for the system being designed whilst having maximum design freedom. At this point, only mission requirements are known whilst the information about how the vehicle and its elements interact is minimum[2].

To mitigate this conundrum, the design process involves making logical and feasible assumptions and using estimates from past projects wherever required. Consequently, the data-sources are used for these approximations and assumptions. In a similar context, since the system design has to integrate primary design disciplines in a feasible solution logic, the analysis methods applied for the involved disciplines must be simple first-order solutions instead of high-fidelity complex methods. Thus, the designer has to be familiar with a set of disciplinary analysis methods that are most suited to the specific system category[3]. Knowledge-based references are primary sources for these disciplinary methods. Coleman[27] emphasizes this sentiment as follows; *"A well organized and condensed Process Library and Disciplinary Methods Library would provide the designer with a quick reference to the tools available, how and when to use them. Such a library would provide the elements for a rapid adaptation of a design process to a new design problem*

[2] see Section 1.2.1, Figure1.10

[3] The data and methods here are selected for the TSTO-VTHL system

*to be solved."* In order to provide such capability, a central library system has been developed to organize and manage pertinent data and knowledge sources.

## 2.1.2 *JABREF Central Library*

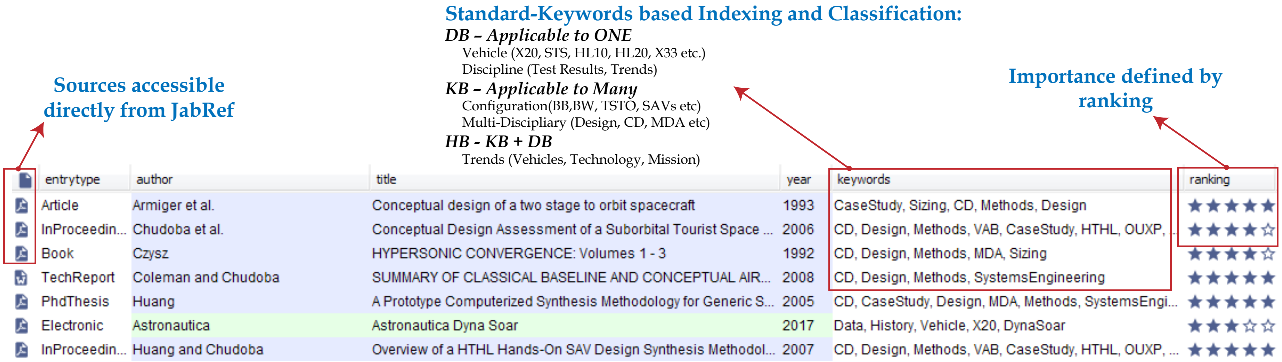
JabRef[4] is an open source bibliography reference management software that is used to organize and manage a central library consisting of more than 600 literature sources[5] relevant to the research domain. All sources are categorized in three major categories depending on the type of information contained in the source, namely; 1) Data, 2) Knowledge or 3) Hybrid. The sources are identified as Data Base (DB) if they are specific to a specific vehicle (eg. test results, performance values, empirical data) while the Knowledge Base sources mainly consist of disciplinary analysis methods and integrating processes that can be applied to more than one case. Hybrid sources contain disciplinary methods as well as vehicle specific data.

The development and management of this central library is an extensive and continuous process that has been maintained throughout this research effort. In order to handle such a large body of information and make available when required, a cataloging management scheme is formulated. All sources are cataloged in JabRef through a set of standard defined keywords identifying the primary information addressed in the source. The following key features and advantages of the JabRef-based central library are the main reasons for its development; they are visualized in Figure 2.4:

THREE TYPES OF SOURCES

| | |
|---|---|
| **KB** | **Methods-Empirical/Analytical, Design Case Studies, MDA, Trade Studies** |
| **DB** | **Data-Empirical/Analytical, Test Results, Specific Vehicle Data** |
| **HB** | **Trends, Heuristics, (DB + KB) Provides Specific Information for individual vehicles and generic methods** |

FIGURE 2.3 – View of JabRef Software and Primary classification of sources.



**Standard-Keywords based Indexing and Classification:**

***DB – Applicable to ONE***
Vehicle (X20, STS, HL10, HL20, X33 etc.)
Discipline (Test Results, Trends)
***KB – Applicable to Many***
Configuration(BB,BW, TSTO, SAVs etc)
Multi-Discipliary (Design, CD, MDA etc)
***HB - KB + DB***
Trends (Vehicles, Technology, Mission)

**Sources accessible directly from JabRef**

**Importance defined by ranking**

| entrytype | author | title | year | keywords | ranking |
|---|---|---|---|---|---|
| Article | Armiger et al. | Conceptual design of a two stage to orbit spacecraft | 1993 | CaseStudy, Sizing, CD, Methods, Design | ★★★★★ |
| InProceedin... | Chudoba et al. | Conceptual Design Assessment of a Suborbital Tourist Space ... | 2006 | CD, Design, Methods, VAB, CaseStudy, HTHL, OUXP, ... | ★★★★☆ |
| Book | Czysz | HYPERSONIC CONVERGENCE: Volumes 1 - 3 | 1992 | CD, Design, Methods, MDA, Sizing | ★★★★☆ |
| TechReport | Coleman and Chudoba | SUMMARY OF CLASSICAL BASELINE AND CONCEPTUAL AIR... | 2008 | CD, Design, Methods, SystemsEngineering | ★★★★★ |
| PhdThesis | Huang | A Prototype Computerized Synthesis Methodology for Generic S... | 2005 | CD, CaseStudy, Design, MDA, Methods, SystemsEngi... | ★★★★★ |
| Electronic | Astronautica | Astronautica Dyna Soar | 2017 | Data, History, Vehicle, X20, DynaSoar | ★★★☆☆ |
| InProceedin... | Huang and Chudoba | Overview of a HTHL Hands-On SAV Design Synthesis Methodol... | 2007 | CD, Design, Methods, VAB, CaseStudy, HTHL, OUXP, ... | ★★★★★ |

FIGURE 2.4 – Features and benefits of JabRef Central Library

- Easy access and storage: JabRef stores all source files in one folder, renames them in a standard template and provides key information on the main screen. Additionally, source files can be accessed directly from JabRef. This reduces time to search for a particular file within the system, all modifications are made on the same file

[4] http://www.jabref.org/

[5] A literature source (or simply a source) refers to a conference proceeding, journal article, technical report, book, or a website

and so, information collected over time is accessible easily for future references.

- Efficient search and sort: All files are indexed using set of standard defined keywords. For example, all disciplinary methods are indexed with the keyword “Method” and the corresponding discipline name. Thus, the combination of keywords “Aerodynamics" and “Method" would display all the aerodynamic methods. This makes searching and organizing tasks much simpler and convenient. Further, addition of ranking scheme helps to identify the sources in order of importance.
- Integration with external softwares: JabRef is easily integrated with softwares like MS Word or Latex and is used to automatically generate bibliography within text documents.
- Quantify literature sources: Standard keywords can be used to quickly scan the overall library and quantify the amount of literature available in each category. Currently the central library holds information for 609 total literature sources. Of these, 151 sources are the knowledge sources, 299 are the data sources and 121 are identified as the hybrid sources, while the rest are not yet classified (being website et al references).
- Expansion of the library: The same basic standards are also used by the other members of the AVD and thus much larger and comprehensive DB is assembled through a collective effort. More than 3000 aerospace literature sources are cataloged collectively by 6 researchers. This serves as a significant advantage where it is possible to collaborate with other researchers, thus covering multiple domains ranging from detailed disciplinary references to the top-level space planning, synthesis, AI et al.

Development of the central library with JabRef is particularly helpful in development of the Data-Base$^{VTHL}$ and Knowledge-Base$^{VTHL}$ systems which are discussed in Section 3.1 in the next chapter. Following next is the review of the TSTO-VTHL class SAS to gain a physical understanding of the primary design elements of the case-study.

## 2.2 *SAS Case-Study Review: TSTO-VTHL*

The topmost level of the SAS hierarchy is the SAS itself, where multiple TSTO-VTHL options are possible as combinations of the various types of LV and LRV stemming from the next lower hierarchy levels. This section addresses the TSTO-VTHL configuration in two parts. The first part discusses the horizontal landing LRV element while the second part focuses on the launch-element.

### 2.2.1 Lifting Reentry Vehicles

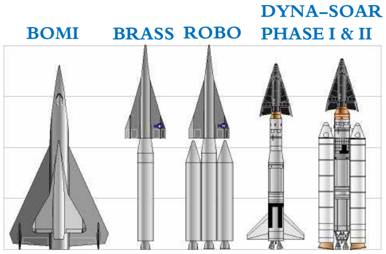


FIGURE 2.5 – Some of the first major LRV programs in the early 1950s. Dyna-Soar was eventually defined as the umbrella-program incorporating the earlier BOMI, BRASS, ROBO and HYWARDS into one single program. Reproduced here from online Encyclopedia Astronautica.

#### *LRV History*

The advantages of horizontally landing a reentry vehicle on a runway like an aircraft were recognized from the very beginning of the space race. The first detailed concept design for an airplane like configuration using a rocket propulsion system to execute space missions was provided by the German space pioneer, Dr. Eugene Sänger in 1933[18]. He named the vehicle Silbervogel, german translation for Silver Bird. Later in the early 1950s, two German scientists, Dr. Walter Dornberger[6] and Dr. Kraft Ehricke, who at the time were working for the Bell Aircraft company in the USA, developed several boost-glide concepts that resulted in the USAF requesting a number of feasibility and design studies[28]. Major space companies of the time proposed several initial studies that resulted in some of the first LRV assessment studies at the industrial level. Bell Aircraft carried out extensive studies under programs like BOMI, BRASS-BELL and ROBO leading to the USAF program HYWARDS in 1956[29]. Following these seminal studies, the 1957 USAF X-20 DynaSoar[7] program [31] was defined that represents the first industry scale effort to develop a LRV, see Figure 2.5. Until its cancellation in 1963 (in wake to give precedence to the Gemini program) the DynaSoar was the biggest industrial aerospace program with a budget of $660 million ($5 billion today), employing more than eight thousand people for over six years.

The following decades have seen numerous multi-billion dollar programs fail to develop an operational LRV, with only a few exceptions. Since then, a vast amount of research and development has been dedicated towards understanding the design and operational requirements of LRVs. However, even after more than six decades of spaceflight, only three spaceplane programs have been able to demonstrate hardware flight status, namely the: US Space Shuttle, USSR Buran and X-37.

#### *Assessment of LRV's Historiography Sources*

A detailed data-base of major lifting reentry projects was compiled to understand the evolution of LRVs and familiarize with the physical characteristic of this SAV class. An initial survey shows clearly that a lot of literature is available directly addressing brief or detailed historical and technical aspects for multiple “spaceplanes“ projects. Some prominent examples of this type of literature are found in the works of Hallion[32–35], Siddiqi[36, 37], Rose[38], Launius et al[39–42] to name a few. These sources could be referred to as the “Historiography“[8] sources for the hypersonic research, do a good job on sum-

---

[6] Both the scientists were taken to the US as part of "Operation Paperclip". Dornberger is supposed to have had the detailed knowledge of Sänger Silbervogel project.

[7] Short for Dynamic Soaring, Dyna-Soar, a contraction of terms ‘Dynamic Ascent‘ and ‘Soaring Flight‘ was to be developed as a space weapon system. Representing a hypersonic glider employing a delta wing body configuration, Dyna-Soar‘s objective was to explore the hypersonic boost-glide technology as applied to a reusable space access system[30]

[8] Definition of *historiography*:
i a : the writing of history; especially : the writing of history based on the critical examination of sources, the selection of particulars from the authentic materials, and the synthesis of particulars into a narrative that will stand the test of critical methods
b : the principles, theory, and history of historical writing
ii : the product of historical writing : a body of historical literature

marizing the major achievements, contributions and goals targeted by each project, and often tends to provide a guideline for researchers to identify those historical projects relevant to their specific research discipline. However, these literature sources are vast and generic in account of the description of legacy projects. The discussion of a project in these accounts is found qualitative in nature while addressing the achievements, lessons learned and technical characteristics of the vehicle and sub-systems. Hence, the importance of a project and the impact on achievements, lessons learned, and data-richness generated is accounted in a stand-alone manner. There is no single account found which attempts to analyze and compare these historical programs against each other whilst providing a quantitative measure of importance of particular projects towards the growth of particular disciplines and its holistic contribution to the hypersonic knowledge base. A consistent assessment of all LRV programs that evaluates these projects against each other is still missing. This sort of assessment is necessary to identify which projects contributed more towards individual disciplines. This lack of analysis presents the opportunity to make an original contribution towards the addressed issue.

The aforementioned hypersonic historiography accounts clearly carry data, information and knowledge of undisputable value, making them invaluable resources towards the formulation of a pragmatic knowledge-capture framework. This kind of framework is found missing that could utilize this invaluable and vast body of knowledge. A prototype system is hence developed that provides a comparative framework to assess, identify and compare the disciplinary contribution and overall importance of selected LRV case-studies. This framework is further utilized to trace the evolution of hypersonic knowledge through the past projects. The following discussion explains the development logic and application of this prototype system as a useful and practical measure that could be significant value to researcher and industry equally.

TABLE 2.1 –
List of Vehicles Surveyed

| **Projects** | **Start Year** | **End Year** | **Organization** | **Manufacturer** |
|---|---|---|---|---|
| **US** | | | | |
| Tsien Spaceplane | 1949 | 1949 | N/A | N/A |
| BOMI | 1952 | 1954 | USAF | Bell |
| BRASS | 1956 | 1956 | USAF | Bell |
| HYWARDS | 1956 | 1957 | USAF | NASA Langley |
| ROBO | 1956 | 1957 | USAF | Bell/Convair/Douglas/NAA |
| X-20 | 1957 | 1963 | USAF | Boeing |
| Alpha Draco | 1957 | 1959 | USAF | Douglas |
| RTTOCV | 1962 | 1964 | NASA | Lockheed/Convair/NAA/Douglas |

*Continued on next page*

TABLE 2.1 – continued from previous page

| Projects | Start Year | End Year | Organization | Manufacturer |
|---|---|---|---|---|
| M2 | 1962 | 1973 | NASA/USAF | Northrop |
| ASSET | 1963 | 1965 | USAF | McDonnell |
| HL-10 | 1964 | 1970 | NASA | Northrop |
| X-23/PRIME | 1965 | 1967 | USAF | Martin |
| X-24A/PILOT | 1965 | 1971 | USAF/NASA | Martin |
| ILRV | 1967 | 1968 | USAF | Lockheed/GD/McDD |
| FDL-5 | 1968 | 1969 | USAF | Lockheed |
| BGRV | 1968 | 1969 | USAF | McDonnell |
| Reentry-F | 1968 | 1968 | NASA | General Electric |
| X-24B/FDL-7 | 1971 | 1973 | USAF/NASA | Martin Marietta |
| STS | 1972 | 2011 | NASA | NorthAmerican/Rockwell |
| X-24C/FDL-8 | 1973 | 1977 | USAF | Lockheed |
| RASV | 1976 | 1977 | USAF | Boeing |
| ALSV | 1979 | 1983 | USAF | Boeing/Rockwell/GD |
| SWERVE | 1979 | 1985 | USAF | Sandia |
| TAV | 1983 | 1995 | USAF | Lockheed/GD/McDD/Rockwell |
| HL-20 | 1988 | 1993 | NASA | Rockwell |
| PioneerPathfinder | 1993 | 2001 | USAF | PioneerRocketplane |
| X-33 | 1995 | 2001 | NASA | Lockheed Martin |
| X-34 | 1995 | 2001 | NASA | OrbitalSciences |
| X-38 | 1995 | 2002 | NASA | ScaledComposites |
| X-37 | 1998 | ongoing | USAF/NASA | Boeing |
| DreamChaser | 2005 | ongoing | NASA | SNC |
| **ESA** | | | | |
| Hermes | 1984 | 1992 | CNES/ESA | Arospatiale/DassaultBreguet |
| FESTIP | 1994 | 1998 | ESA | N/A |
| PRE-X | 2000 | ongoing | CNES | EADS-LV |
| Phoenix | 2000 | 2004 | ASTRA | Pacific-American |
| EXPERT | 2002 | ongoing | ESA | ThalesAlenia |
| USV | 2004 | ongoing | ESA/CIRA | CIRA |
| SOCRATES | 2004 | N/A | ESA | ESA/DLR |
| IXV | 2005 | ongoing | ESA | ThalesAlenia |
| **GERMANY/UK** | | | | |
| Silverbogel | 1933 | 1942 | N/A | N/A |
| Whitworth Pyramid | 1954 | 1960 | N/A | N/A |
| JunkersRT-8 | 1961 | 1969 | Junkers | Junkers |
| MUSTARD | 1962 | 1968 | BAC | BAC |
| BUMERANG | 1967 | 1974 | ERNO | ERNO |
| SangerII/HORUS | 1985 | 1995 | MBB | MBB |
| PLATO | 1987 | 1990 | MBB-ERNO | MBB-ERNO |
| **JAPAN** | | | | |
| OREX | 1994 | 1994 | JAXA | NASDA |
| HYFLEX | 1996 | 1996 | JAXA | Mitsubishi |
| AFLEX | 1996 | 1996 | JAXA | Mitsubishi |
| HSFD | 2000 | 2004 | JAXA | Mitsubishi |
| **SOVIET** | | | | |
| VKA-23 | 1956 | 1959 | OKB-23 | Myasishchev |
| OKB-Racketoplan | 1959 | 1962 | OKB-53 | Chelomey |
| SPIRAL-OS | 1962 | 1975 | OKB-155 | Mikoyan |
| Mig-105 | 1976 | 1978 | USSR Air Force | Mikoyan |
| BURAN | 1976 | 1988 | NPO Molnia | Mikoyan |

*Continued on next page*

TABLE 2.1 – continued from previous page

| Projects | Start Year | End Year | Organization | Manufacturer |
|---|---|---|---|---|
| BOR-4 | 1980 | 1984 | NPO Molnia | NPO-Molnia |
| LKS | 1980 | 1983 | Chelomey | Chelomey |
| MAKS | 1988 | 1991 | NPO Molniya | NPO-Molniya |
| ORYOL | 1993 | 2001 | RSA | RSA |
| KLIPPER | 2004 | 2007 | RSA | RSC-Energia |

*Logic description for the AHP based quantitative analysis of 60 LRV projects*

An analytical model representing the literature sources is developed next that addresses a total of 60 cases of LRV projects undertaken by the major space agencies and organizations world-wide, see Table 2.1. The historiograhy literature sources are first used to develop a structured Data-Base of the 60 LRV projects where the qualitative information is organized in a structured format identifying major details of the disciplinary subsystems, the major accomplishments and primary goals for each project, see Figure 2.6. This information is then utilized to develop a numerical framework where the vehicles are assessed for disciplinary contribution as the significance of each project is recognized for the involved disciplines. These case-studies are analyzed using an analytical method, developed by modifying the traditional Analytic Hierarchy Process (AHP) technique. The AHP is an effective technique developed by Thomas Saaty[43] in 1980 to deal with the problems encountered in complex decision making. The basic concept is to breakdown a complex decision into a series of simpler decisions. This type of approach is particularly useful for analyzing problems where qualitative and non-tangible aspects are of significant worth.

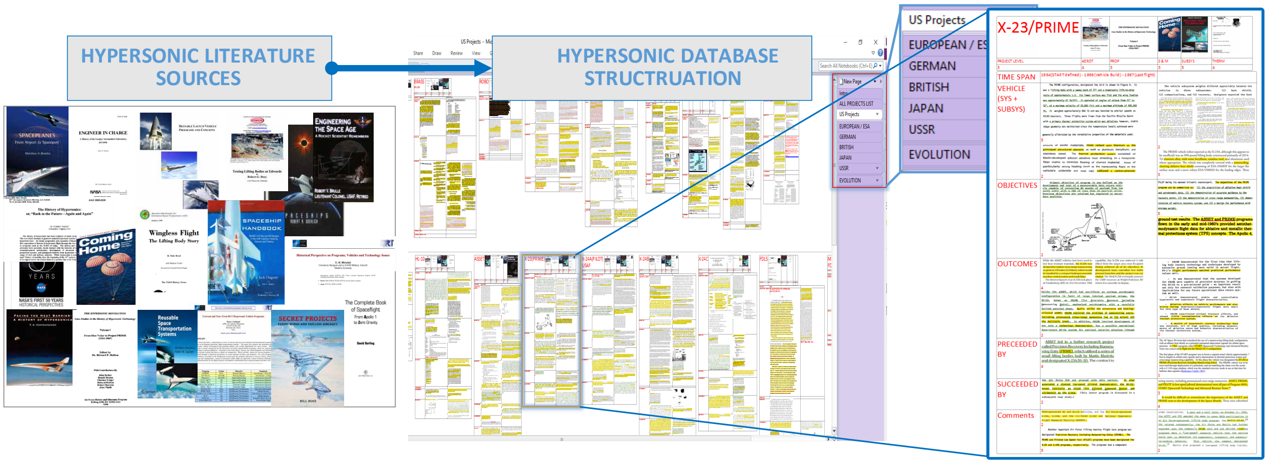


FIGURE 2.6 – Hypersonic historiography sources are used to develop a Data-Base for the LRV vehicles which provides a structured assortment of the qualitative information addressed in the sources.

The AHP captures the qualitative essence and provides a measurable quantitative framework which enables consistent informed decisions.

AHP is applied in situations where a set of alternatives[9] are evaluated based on certain evaluation criteria. Through a pair-wise comparison among all the 'n' number of criteria, an 'n x n' comparison matrix is developed. By first normalizing the matrix and then averaging each row, eigen values and eigen vector assessment is performed to determine the weight of each criteria. This process enforces a consistency check on the criteria weight to avoid any user-defined bias among the evaluation criteria. If this consistency check is not met, the initial comparison matrix has to be to re-evaluated. Alternative's scores are also calculated through the same process. These two steps, though similar in execution, are independent of each other. The global score for each alternative is now used to select the best alternative. A detailed explanation of the this process is found by Satty in reference[43].

» *Defining evaluation criteria for the AHP model:* A space access vehicle is a multi-disciplinary system, where constituent sub-systems integrate cohesively to perform a mission as per the program requirements. The legacy projects being assessed here could be broadly categorized as either technology oriented[10] or vehicle oriented[11]. It is observed that the primary disciplines involved in design of space access vehicles serve as suitable criteria. These disciplines are the basis of most technology oriented programs and are also the building blocks of a SAS design. By defining the disciplines as evaluation criteria, it will be possible to distinctly recognize the contribution of each case-study towards an individual discipline. Technology development programs, which tend to focus on one or two disciplines, would receive high scores for those disciplines.

At the same time, it is also necessary to consider the quality and depth of research achieved by a case-study. To include this factor in the model, an additional criterion is added based on the life-cycle stage reached by the case-study.

Hirschel[44] provides a list of requirements on classical hypersonic disciplines, defined for the FESTIP Technology and Development Plan[45]. Based on this list, five primary hypersonic disciplines are identified as disciplinary evaluation criteria for the current model. Definition of these criteria is selected form Hirshel[44], and modified to suit the current study. A sixth criterion is selected to identify the progress of a project at a systems level. The six evaluation criteria are defined below:

1. **Disciplinary Criteria**[12]

   i. *Aerothermodynamics:* aerodynamic performance, configuration flyability qualities, propulsion/airframe integration, (upper) stage

---

[9] In current context, alternatives are the 60 LRV case-studies that are being assessed through AHP.

[10] Technology oriented projects are defined with the primary goal of developing technology related to one specific discipline. These are usually experimental vehicles where only one or two subsystems are of main interest.

[11] Vehicle oriented programs are defined with the primary goal of developing an operational vehicle and hence have to consider all subsystems equally.

[12] These address the disciplinary subsystems found at hierarchy level-3 of the SAS.

integration and separation for TSTO-systems, loads determination, surface properties determination.

ii. *Structures and materials:* structural topology, light-weight primary structures, hot stabilisation and control surfaces, cryotank structures(integrated/non-integrated), materials, coatings, joints, seals.

iii. *Propulsion:* propulsion system performance analysis, weight, reusability, throttleability (landing engines), restartability, fuel consumption, propulsion/airframe integration, net thrust, cooling (inlet, core engine, nozzle).

iv. *Stability and Instrumentation:* flight mechanics/dynamics, stability and controllability, flight control system, air-data system, general instrumentation, actuator systems, guidance navigation and control, stage separation system for TSTO-systems, onboard power generation.

v. *Thermal management:* TPS addressed, heating analysis, passive (surface radiation) cooling, internal insulation, active cooling (internal, external), thermal household of CAV-type vehicles.

2. **System-Level Criteria**[13]

vi. *Project Level:* paper study, ground test, flight test, technology demonstrator, operational vehicle.

These six evaluation criteria are the parameters to judge the selected group of case studies. Each disciplinary criteria is defined as a group of specific analysis requirements to easily identify the research progress achieved by a case-study in every discipline. By following this definition pattern, every case-study can be consistently scored for a criterion by matching the number of analysis requirement satisfied by that case-study. This rationale is further explained in following sub-section.

» *Defining Scoring-Metric for assessing case-studies:* According to the standard AHP technique, every case-study must be scored through a pair-wise comparison with other candidates, for each evaluation criteria. Doing so establishes a consistent measure by breaking the complex decision involving all alternatives, into a series of easy decisions among two alternatives at a time. Such pairwise comparison breakdown is easily applicable for a small model where the number of combinations of criteria and alternatives is relatively limited. For an AHP model, if 'A' is the number of alternatives and 'C' is the number of criteria, then the total 'N' pair-wise decisions among alternatives is calculated as:

$$N = C * (A^2/2 - A) \tag{2.1}$$

---

[13] This criterion address the systems-level contribution found at hierarchy level-2 of the SAS. As a result, this criteria takes into account the effect of the integration of subsystems.

Clearly, the total number of pairwise decisions grows exponentially with the number of alternatives. For the current study where the model is composed of 6 evaluation criteria and 60 LRV case-studies as alternatives to be measured, the total number of pairwise decision becomes 10,440. To mitigate this overwhelming task of comparing one case-study against others, a simplistic approach is adopted where all the case studies are scored against a standard baseline. In this manner, all the case studies are measured consistently requiring a short turnaround time, given the reference point is clearly and distinctly defined.

This baseline is established through a scoring metric based on the definition of the evaluation criteria. A scoring scale is defined for all six criteria such that a higher score indicates that the alternative meets most analysis requirements from the criteria definition. The scoring metric is given in Table 2.2 describing what each score entails for a criterion.

| Score | Disciplinary Criteria Description | System-Level Criteria Description |
|---|---|---|
| 1 | Discipline not evaluated in case-study<br>Meets no definition requirements<br>No impact on the project | Paper Study: Preliminary design analysis performed, data not available to confirm existence of ground tests hardware |
| 2 | Minimal impact on the project<br>Minimal definition requirements<br>Not important for the project | Ground Test: Detailed design analysis supported by ground-test articles dedicated for specific disciplines(Wind Tunnel Models, Simulator etc.) |
| 3 | Satisfy all definition requirements<br>Not important for the project<br>Not gained anything new<br>Used off-the-shelf technology | Flight Test: Program carried out flight tests focusing on design-tool validation dedicated for specific disciplines (Scaled Flight Test Model) |
| 4 | Satisfy all definition requirements<br>Has a major impact on the project<br>Significant results gained<br>Uses state-of-art technology<br>Influence on future programs | Technology Demonstrator: Scaled version of the targeted operational vehicle, focusing on the integration and validation of key technologies at systems level |
| 5 | Satisfy all definition requirements<br>Key discipline driving the project<br>Breakthrough results gained<br>State-of-art technology development<br>Project significant to discipline's growth<br>New lessons learned<br>Directly applied to future programs | Operational Vehicle: Vehicle ready to perform transpiration tasks from orbit and back. Only three vehicles from the case-studies have reached operational level(US Space Shuttle, USSR Buran and X-37). |

TABLE 2.2 –
Case-Studies Scoring Metric

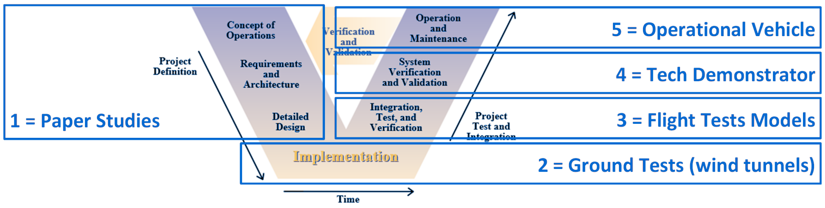


FIGURE 2.7 – Project-Level criteria is defined based on the life-cycle stage achieved by the program.

Scoring scale for the systems criteria (“Project Level") is relatively much easier to understand and implement than disciplinary criteria.As seen in Figure 2.7, this criteria follows the product life-cycle stages, represented here by a standard V-Model[46]. The disciplinary criteria are scored based on the multiple factors, like the level of research effort addressed by a case-study for the discipline, impact of the discipline on the case study, contributions of the case-study to discipline‘s knowledge growth etc. So, for a case-study where CFD analysis of the vehicle is performed, it would get a higher score in ’Aerothermodynmics’ criteria over another case-study where the aerodynamics analysis is limited to a basic lift-drag polar.

In order to appropriately score the disciplinary criteria, every case-study is examined thoroughly by reviewing the available information for every discipline. This goal is achieved by an exhaustive literature survey, followed by structured organization of the information. For this purpose, the hypersonic database is developed from the historiography sources as explained earlier, see Figure 2.6.

» *Determination of Evaluation Criteria Weights*: For the traditional AHP technique, the criteria weight is evaluated by a user-defined, pairwise comparison among evaluation criteria. The complexity of this particular study lies in defining the importance among disciplinary criteria, as a specific discipline could be important in one project while not equally important for the other. An example of this difference is seen in case-studies like ASSET and PILOT, both part of the same START program[40] but with very different mission requirements and thus different vehicle designs. The ASSET project was aimed to develop aerothermodynamics and structures & materials for X-20 program[32]. On the other hand, PILOT or X-24A explored the problem of maneuvering entry to demonstrate stable and controllable flight characteristics[32]. While assigning criteria scores for both these case-studies, ASSET is scored highly for ’aerothermodynamics’, ’structures & materials’ and ’thermal management’ disciplines while PILOT is scored highly for ’stability and instrumentation’. Similarly, every case-study has specific requirements, mission objectives and operational constraints which dictate the level of involvement and growth for different disciplines. Therefore, one disciplinary criteria cannot be arbitrarily assigned more or less important than another, as it would create a inherent unjustified bias in the evaluation model. To resolve this complexity, a different approach has been taken to generate the initial comparison matrix, than the standard AHP process of manually assigning one criteria more important than other. The mathematical process following this first step is the same as implemented in the AHP logic, which enforces the consistency check on the final criteria weights.

The criteria defined for this study are classified into two broad categories: (1) Systems-Level criteria and (2) Disciplinary criteria. 'Project level' criteria being a systems-level factor, is held three times[14] more important than disciplinary criteria, which are representative of subsystem advancement. To develop the comparison matrix among disciplines, every case-study is scored for all disciplinary criteria and a cumulative total is calculated for each discipline. Since the disciplinary criteria score for a case-study represents the contribution and significance of that discipline, the cumulative scores thus represents the overall research effort of all case-studies towards a discipline. As a result, cumulative discipline scores reflect the trend shown by the case-studies throughout the evolution of the hypersonic knowledge base and are used to make pair-wise relations among disciplines that leads to the first set of criteria weight based on an acceptable consistency check. The first iteration of the criteria weighs are used again, combined with the disciplinary case studies scores to implement a feedback loop and provide a second iteration of criteria weights. These weights are used as the final criteria weights while executing the AHP process. The priority among criteria is then established as reflected in the final weights. The final calculated weights are then calculated as follows:

1. **System-Level Criteria**
    i. *Project Level = 0.308*
2. **Disciplinary Criteria**
    ii. *Aerothermodynamics = 0.157*
    iii. *Structures and materials = 0.114*
    iv. *Propulsion = 0.132*
    v. *Stability and Instrumentation = 0.136*
    vi. *Thermal management = 0.144*

where it can be seen that Project Level is assigned maximum weight over other disciplinary criteria, while the five disciplinary criteria are relatively close to each other as indicated by the cumulative discipline scores.

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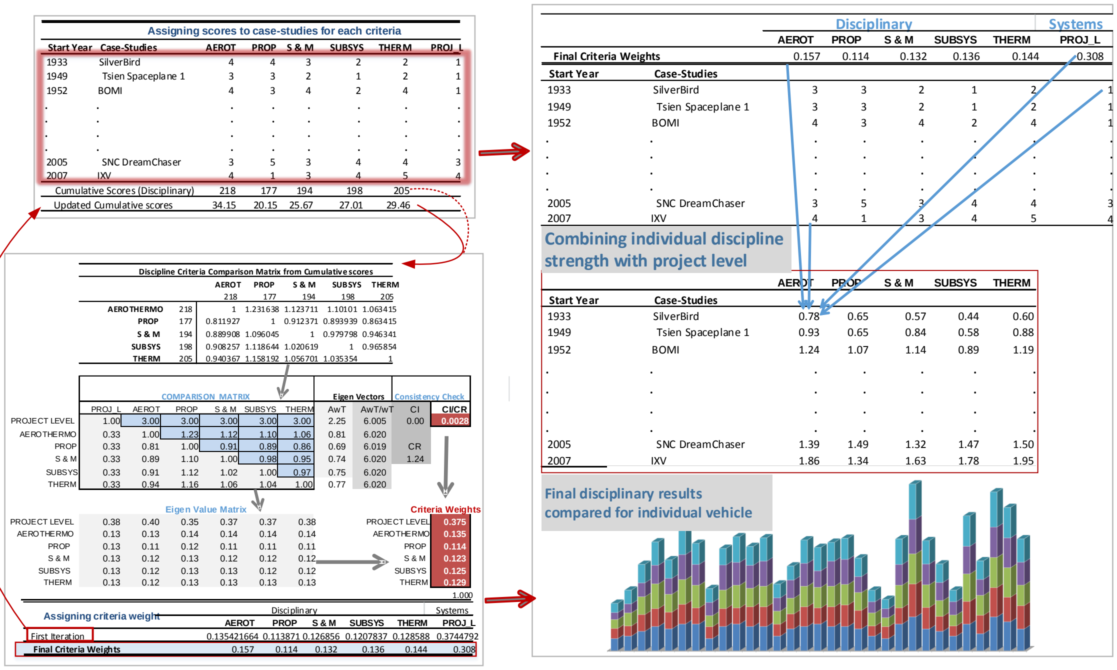
[14] This factor was selected after several iterations of trial and error until the AHP process cleared the consistency check.



**Assigning scores to case-studies for each criteria**

| Start Year | Case-Studies | AEROT | PROP | S & M | SUBSYS | THERM | PROJ_L |
|---|---|---|---|---|---|---|---|
| 1933 | SilverBird | 4 | 4 | 3 | 2 | 2 | 1 |
| 1949 | Tsien Spaceplane 1 | 3 | 3 | 2 | 1 | 2 | 1 |
| 1952 | BOMI | 4 | 3 | 4 | 2 | 4 | 1 |
| . | . | . | . | . | . | . | . |
| . | . | . | . | . | . | . | . |
| . | . | . | . | . | . | . | . |
| . | . | . | . | . | . | . | . |
| 2005 | SNC DreamChaser | 3 | 5 | 3 | 4 | 4 | 3 |
| 2007 | IXV | 4 | 1 | 3 | 4 | 5 | 4 |
| Cumulative Scores (Disciplinary) | | 218 | 177 | 194 | 198 | 205 | |
| Updated Cumulative scores | | 34.15 | 20.15 | 25.67 | 27.01 | 29.46 | |

**Discipline Criteria Comparison Matrix from Cumulative scores**

| | | AEROT | PROP | S & M | SUBSYS | THERM |
|---|---|---|---|---|---|---|
| | | 218 | 177 | 194 | 198 | 205 |
| **AEROTHERMO** | 218 | 1 | 1.231638 | 1.123711 | 1.10101 | 1.063415 |
| **PROP** | 177 | 0.811927 | 1 | 0.912371 | 0.893939 | 0.863415 |
| **S & M** | 194 | 0.889908 | 1.096045 | 1 | 0.979798 | 0.946341 |
| **SUBSYS** | 198 | 0.908257 | 1.118644 | 1.020619 | 1 | 0.965854 |
| **THERM** | 205 | 0.940367 | 1.158192 | 1.056701 | 1.035354 | 1 |

| | COMPARISON MATRIX | | | | | | Eigen Vectors | | Consistency Check | |
|---|---|---|---|---|---|---|---|---|---|---|
| | PROJ_L | AEROT | PROP | S & M | SUBSYS | THERM | AwT | AwT/wT | CI | CI/CR |
| PROJECT LEVEL | 1.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 2.25 | 6.005 | 0.00 | 0.0028 |
| AEROTHERMO | 0.33 | 1.00 | 1.23 | 1.12 | 1.10 | 1.06 | 0.81 | 6.020 | | |
| PROP | 0.33 | 0.81 | 1.00 | 0.91 | 0.89 | 0.86 | 0.69 | 6.019 | CR | |
| S & M | 0.33 | 0.89 | 1.10 | 1.00 | 0.98 | 0.95 | 0.74 | 6.020 | 1.24 | |
| SUBSYS | 0.33 | 0.91 | 1.12 | 1.02 | 1.00 | 0.97 | 0.75 | 6.020 | | |
| THERM | 0.33 | 0.94 | 1.16 | 1.06 | 1.04 | 1.00 | 0.77 | 6.020 | | |

Eigen Value Matrix

| | | | | | | |
|---|---|---|---|---|---|---|
| PROJECT LEVEL | 0.38 | 0.40 | 0.35 | 0.37 | 0.37 | 0.38 |
| AEROTHERMO | 0.13 | 0.13 | 0.14 | 0.14 | 0.14 | 0.14 |
| PROP | 0.13 | 0.11 | 0.12 | 0.11 | 0.11 | 0.11 |
| S & M | 0.13 | 0.12 | 0.13 | 0.12 | 0.12 | 0.12 |
| SUBSYS | 0.13 | 0.12 | 0.13 | 0.13 | 0.12 | 0.12 |
| THERM | 0.13 | 0.12 | 0.13 | 0.13 | 0.13 | 0.13 |

Criteria Weights

| | |
|---|---|
| PROJECT LEVEL | 0.375 |
| AEROTHERMO | 0.135 |
| PROP | 0.114 |
| S & M | 0.123 |
| SUBSYS | 0.125 |
| THERM | 0.129 |
| | 1.000 |

**Assigning criteria weight**

| | Disciplinary | | | | | Systems |
|---|---|---|---|---|---|---|
| | **AEROT** | **PROP** | **S & M** | **SUBSYS** | **THERM** | **PROJ_L** |
| First Iteration | 0.135421664 | 0.113871 | 0.126856 | 0.1207837 | 0.128588 | 0.3744792 |
| **Final Criteria Weights** | 0.157 | 0.114 | 0.132 | 0.136 | 0.144 | 0.308 |

| | | Disciplinary | | | | | Systems |
|---|---|---|---|---|---|---|---|
| | | **AEROT** | **PROP** | **S & M** | **SUBSYS** | **THERM** | **PROJ_L** |
| **Final Criteria Weights** | | 0.157 | 0.114 | 0.132 | 0.136 | 0.144 | 0.308 |
| **Start Year** | **Case-Studies** | | | | | | |
| 1933 | SilverBird | 3 | 3 | 2 | 1 | 2 | 1 |
| 1949 | Tsien Spaceplane 1 | 3 | 3 | 2 | 1 | 2 | 1 |
| 1952 | BOMI | 4 | 3 | 4 | 2 | 4 | 1 |
| . | . | . | . | . | . | . | . |
| . | . | . | . | . | . | . | . |
| . | . | . | . | . | . | . | . |
| . | . | . | . | . | . | . | . |
| 2005 | SNC DreamChaser | 3 | 5 | 3 | 4 | 4 | 3 |
| 2007 | IXV | 4 | 1 | 3 | 4 | 5 | 4 |

**Combining individual discipline strength with project level**

| | | **AEROT** | **PROP** | **S & M** | **SUBSYS** | **THERM** |
|---|---|---|---|---|---|---|
| **Start Year** | **Case-Studies** | | | | | |
| 1933 | SilverBird | 0.78 | 0.65 | 0.57 | 0.44 | 0.60 |
| 1949 | Tsien Spaceplane 1 | 0.93 | 0.65 | 0.84 | 0.58 | 0.88 |
| 1952 | BOMI | 1.24 | 1.07 | 1.14 | 0.89 | 1.19 |
| . | . | . | . | . | . | . |
| . | . | . | . | . | . | . |
| . | . | . | . | . | . | . |
| . | . | . | . | . | . | . |
| 2005 | SNC DreamChaser | 1.39 | 1.49 | 1.32 | 1.47 | 1.50 |
| 2007 | IXV | 1.86 | 1.34 | 1.63 | 1.78 | 1.95 |

**Final disciplinary results compared for individual vehicle**

FIGURE 2.8 – Iterative process applied to obtain the weights of evaluation criteria and application of criteria weight and alternatives scores in the AHP model.

» *Developement of the Analytical Model and Evaluation Logic applied for the LRV case-studies:* At this point, all elements are in place to execute the AHP model. Every case-study is scored for all six evaluation criteria and final criteria weights are established. Case-study scores are multiplied by criteria weight for every criteria and added together to calculate a global score for every case-study. This score is indicative of the holistic contribution of every case-study towards hypersonic knowledge evolution. The model schematic is shown in Figure 2.8 where the information flow is visualized throughout the AHP process leading to the final comparative results for every case-study.

The AHP results could be used to analyze and compare case-studies for individual disciplines through which, a discipline-oriented researcher could visualize the most important historical programs for his own advantage. At the same time, the global score indicate holistic effects and importance of a program towards hypersonic knowledge evolution. A discipline-based global score is calculated next, such that the effect of the 'Project Level' criteria is distributed equally among the disciplines. This discipline-based global score is calculated as:

$$D_{Global-Score} = D_{Score} * D_{Weight} + P_{Score} * P_{Weight}/5 \qquad (2.2)$$

where D refers to a disciplinary criteria and P refers to Project-Level

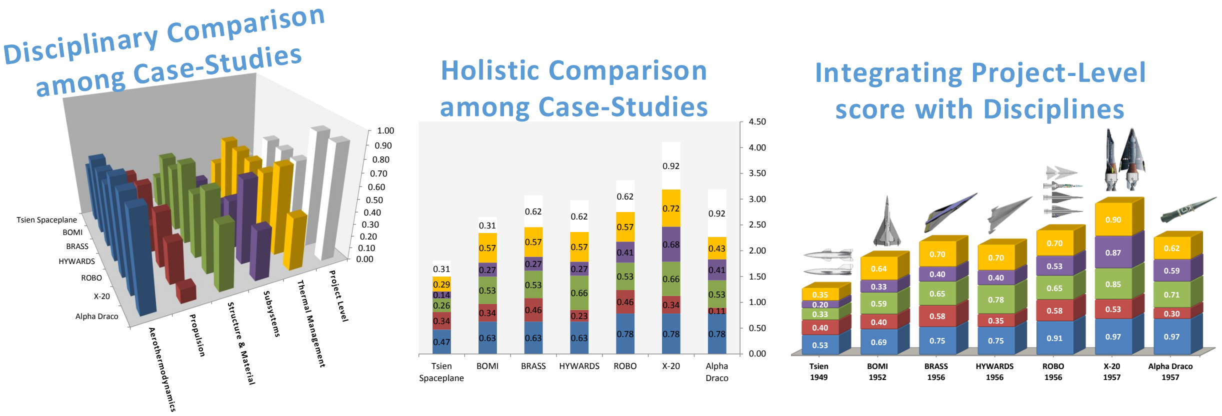


FIGURE 2.9 – The disciplinary and global results can be visualized to make disciplinary and holistic comparisons among the case-studies thus providing a substantial insight into LRV history overall and individual programs in specific.

criteria. With this implementation, the global score for a case-study stays the same but the case-study could now be effectively represented as composed of only primary disciplines, see Figure 2.9. It must be noted here that the primary significance of this assessment is to not judge a program's discipline in its entirety but rather on a comparative basis where the significance is justified when looked at other disciplines in the program or compared with other programs for the same discipline.

This concludes the explanation of the AHP model setup which was used to develop quantitative comparative assessments for all 60 case-studies.

» *AHP quantitative assessment results:* The results of the quantitative assessment from the AHP model are shown next in a visual graphics form to provide a quick summary of significance and contribution for each program for the assessed disciplines. As mentioned earlier, the numerical results represents the significance and relevance of the particular program in the related disciplines. Detailed explanation for scores and the related programs is further provided in the Appendix A.

Figure 2.10 shows the quantitative results for the US based LRV programs comparing case-studies for the disciplinary factors. It must be noted that the discipline scores are combined with project-level criteria and hence the projects that reached advanced life-cycle stage are scored higher for disciplinary criteria as well. This shows an overall comparison of the case-studies.

On the same basis, AHP scores of other other international LRV programs are further shown in Figure 2.11. In addition to the quantitative

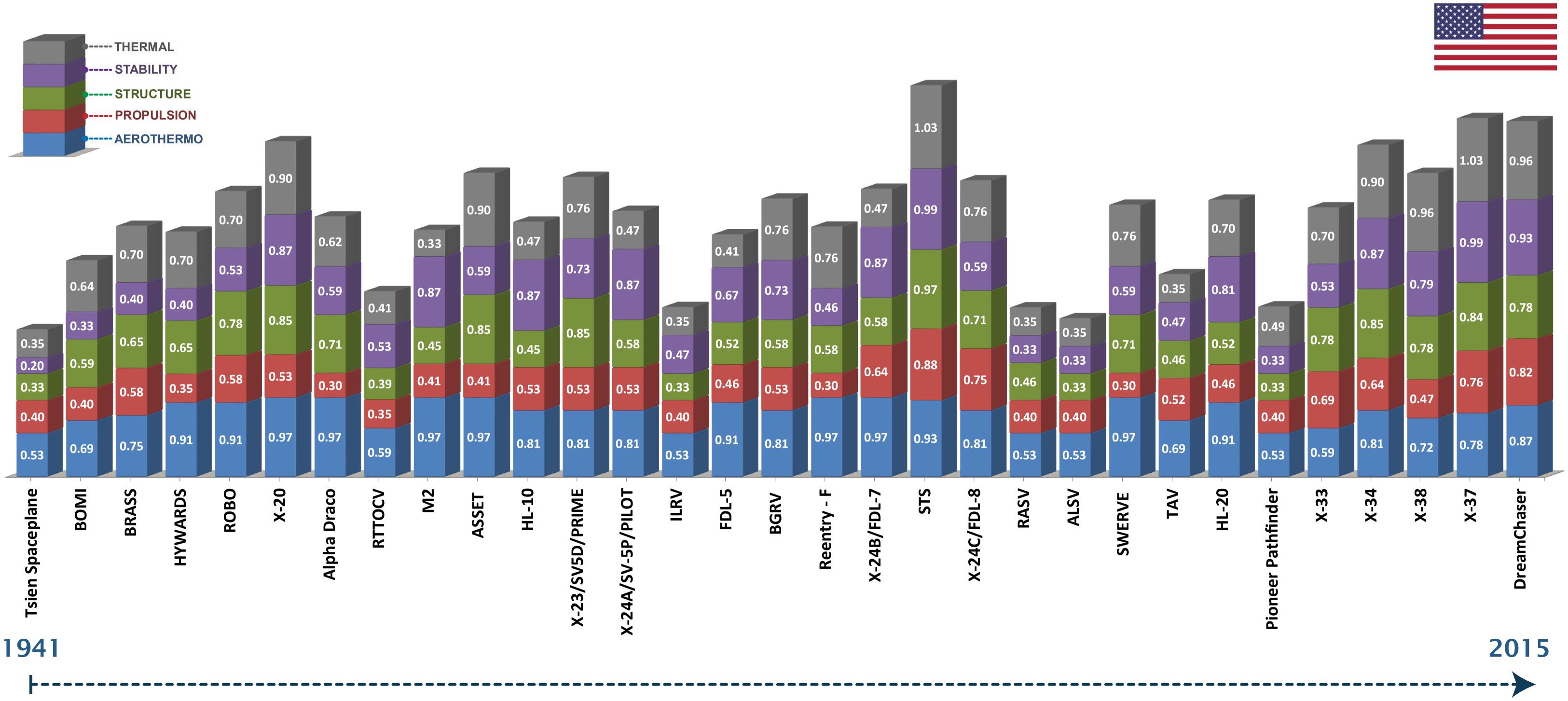


FIGURE 2.10 –
AHP results showing a quantitative disciplinary comparison for the US based major LRV programs and concepts from 1941 to present.

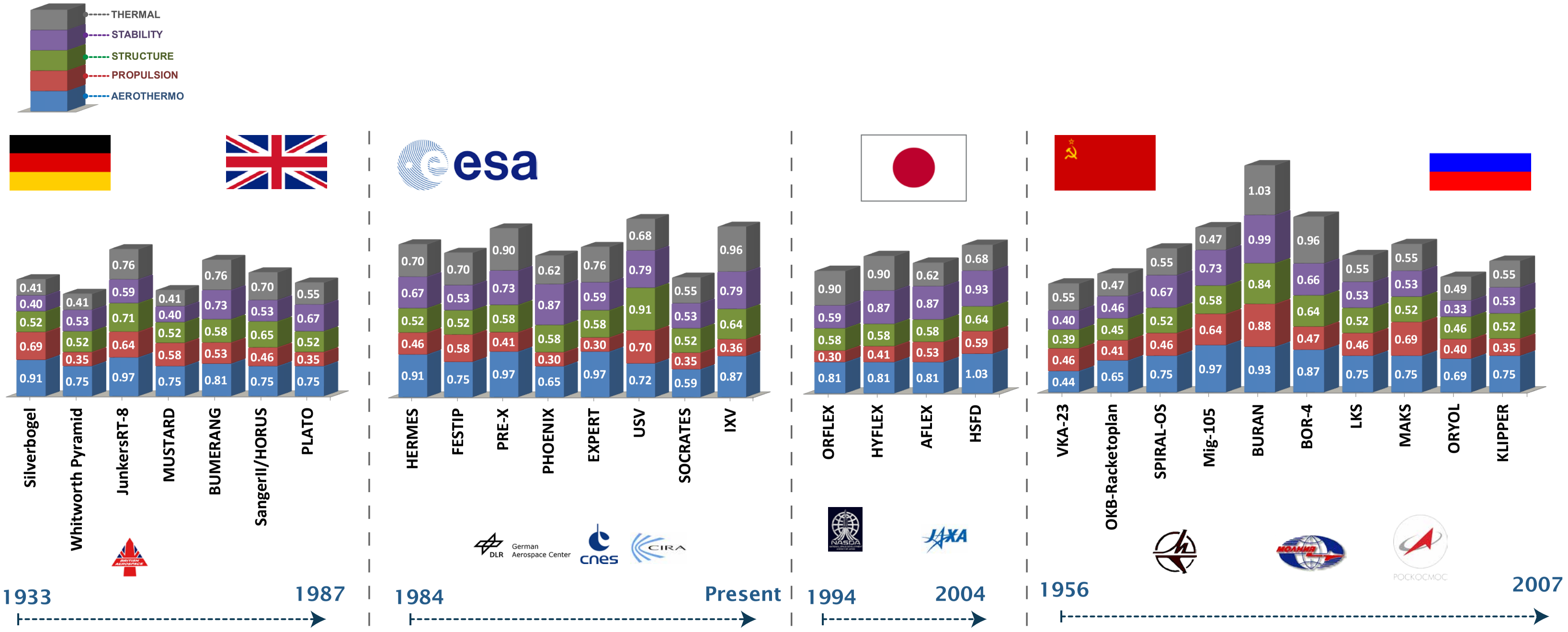


FIGURE 2.11 –
AHP results showing a quantitative disciplinary comparison for the major international LRV programs.

results, the comprehensive review of the LRV vehicles also showed significant interconnections and overlapping occurring in these programs throughout the history. Most programs were undertaken simultaneously or in a sequence to advance the knowledge of hypersonic flight and advance enabling technologies. This trend is recognized by tracking the evolution of these programs in the following series of Figures for each group. This helps to visualize how the programs utilized knowledge gained in the past and helped advance the state of the art in technical and design domain.

» *Multi-disciplinary design integration assessment:* The main focus of the AHP model has been to assess disciplinary specialization of the LRV case-studies. Developing this analytical framework required an extensive literature review followed by development of a structured data-base specific for each case-study. It was found that the information available for the US based programs in public domain include a wider body of literature than other international case-studies. Most sources found were related to the DD or PD phase results, while the CD phase was found weak on the available literature in public domain. These literature sources are where the initial design decisions related to selection of vehicle configuration and subsystem technologies could be found. As a result, a secondary survey was conducted only for the US based LRV programs where the main focus was to access the amount of information available for CD phase. To measure the CD phase related information, following set of information criteria were defined that are characteristic of the CD phase assessment.

i. *DI:* Information available related to the design phases.

ii. *DR:* Information available related to the individual disciplines.

iii. *DM:* Information available related to the disciplinary analysis methods.

iv. *MDA:* Information available related to the muldi-disciplinary analysis and disciplinary integration logic.

v. *SZ:* Information available related to the sizing logic implemented in the MDA.

vi. *SS:* Information related to the solution space development showing alternate design concepts and solution space assessed during the CD phase.

Since most documentation found for the case-studies is restircted to the detailed design or hardware data, a measuring scale was defined to distinguish if a literature source address the above defined information

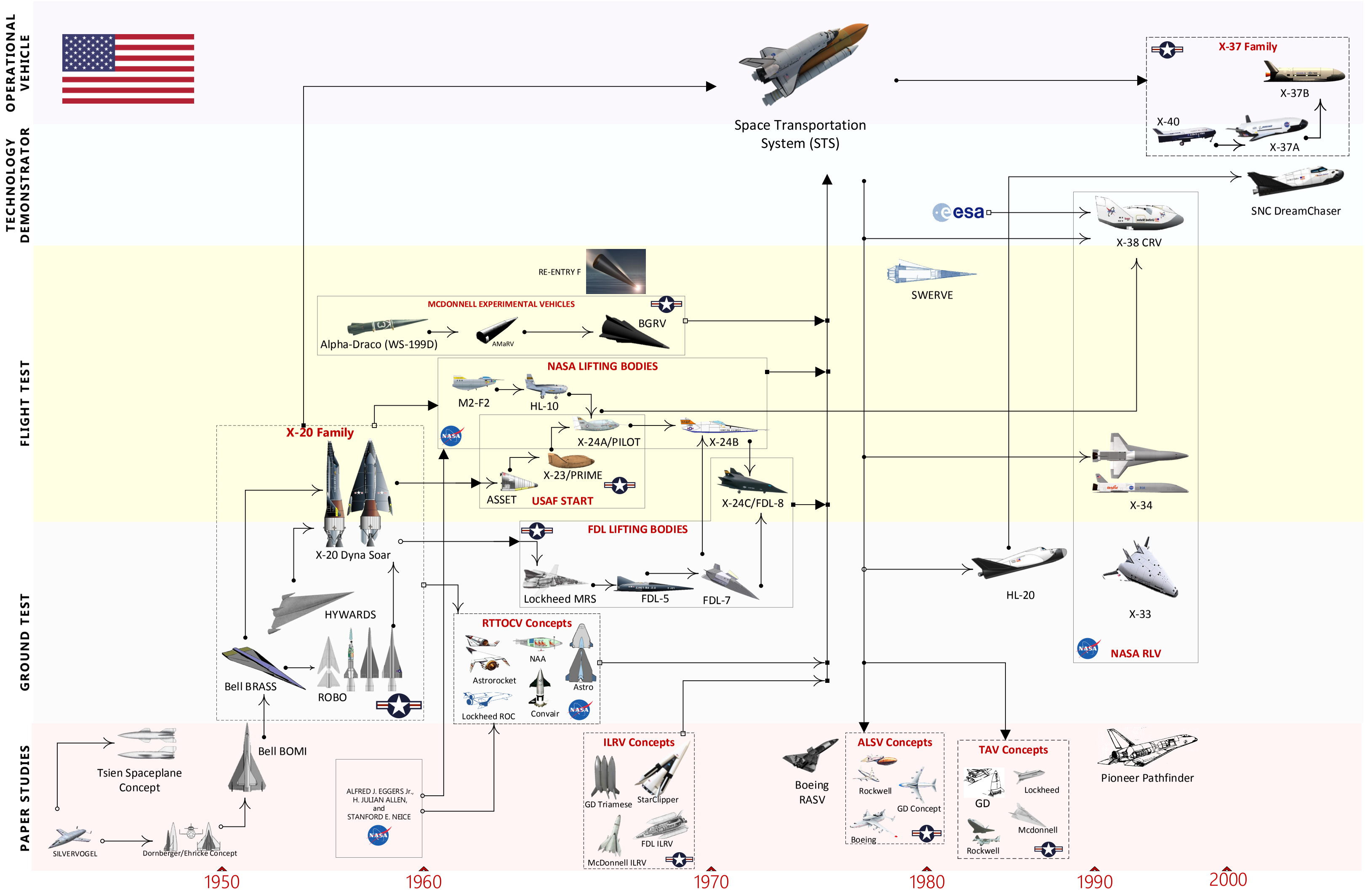


FIGURE 2.12 –
Evolution of LRV programs in the USA.

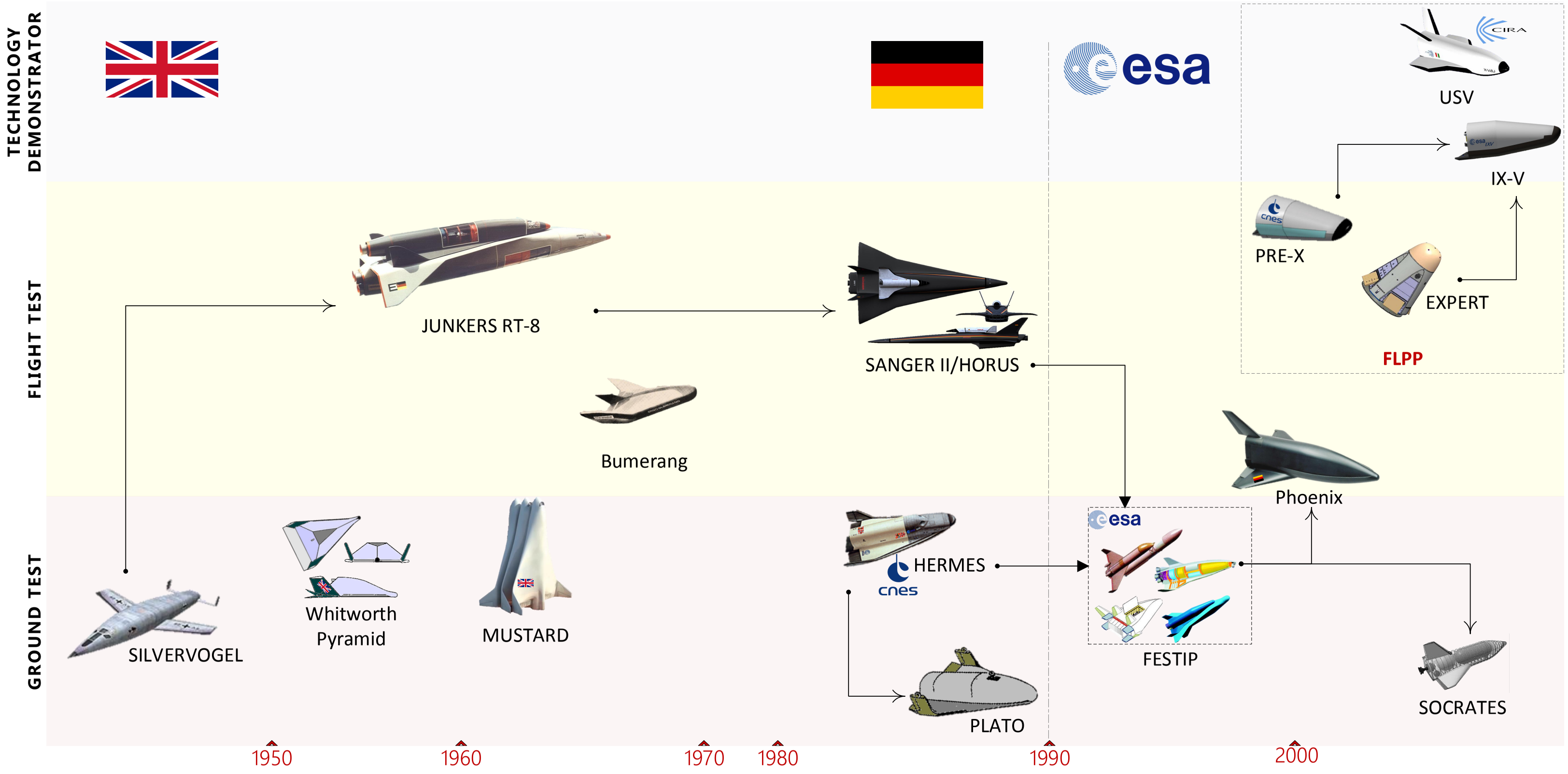


FIGURE 2.13 –
Evolution of LRV programs in Europe.

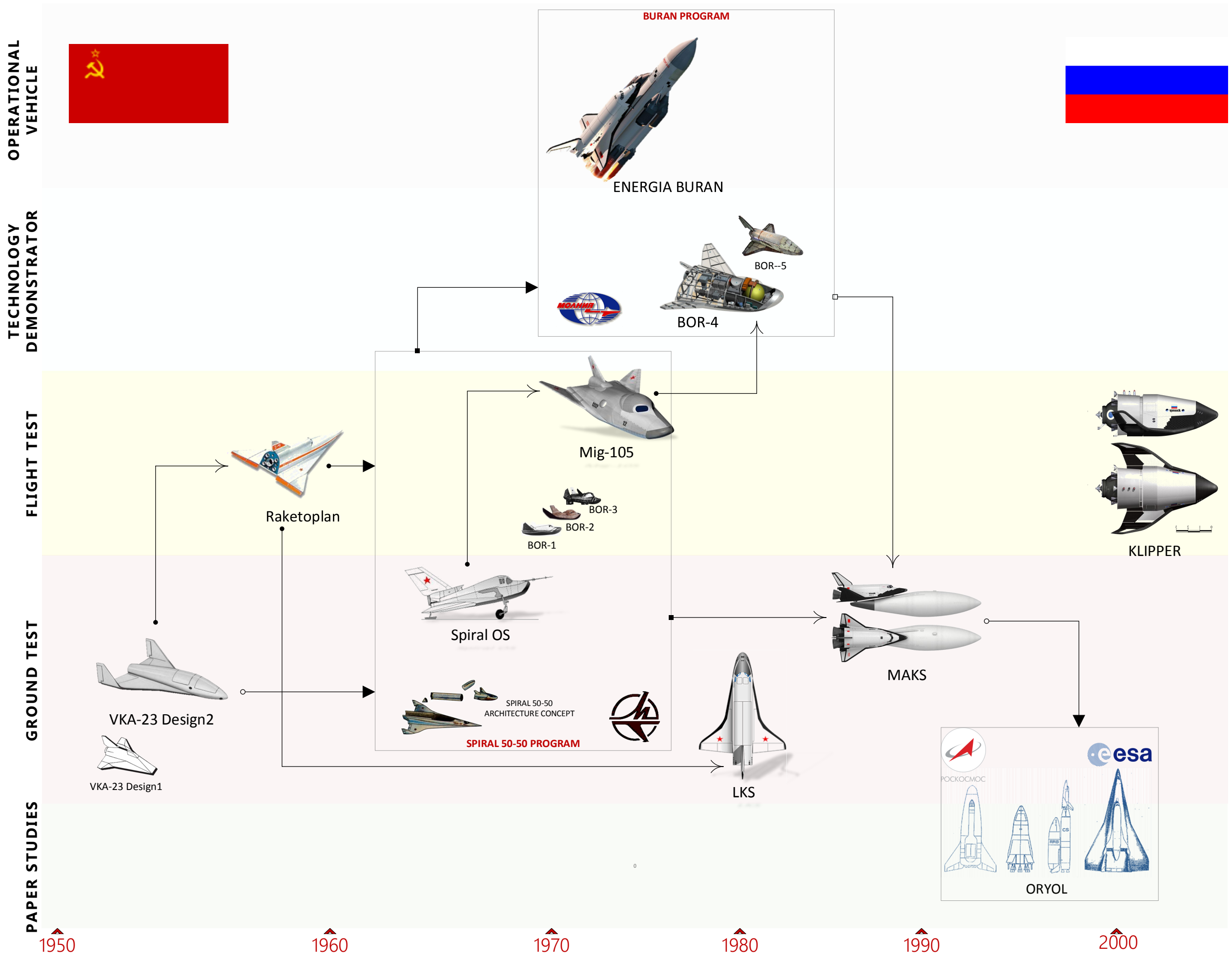


FIGURE 2.14 – Evolution of LTV programs in Soviet Union and Russia.

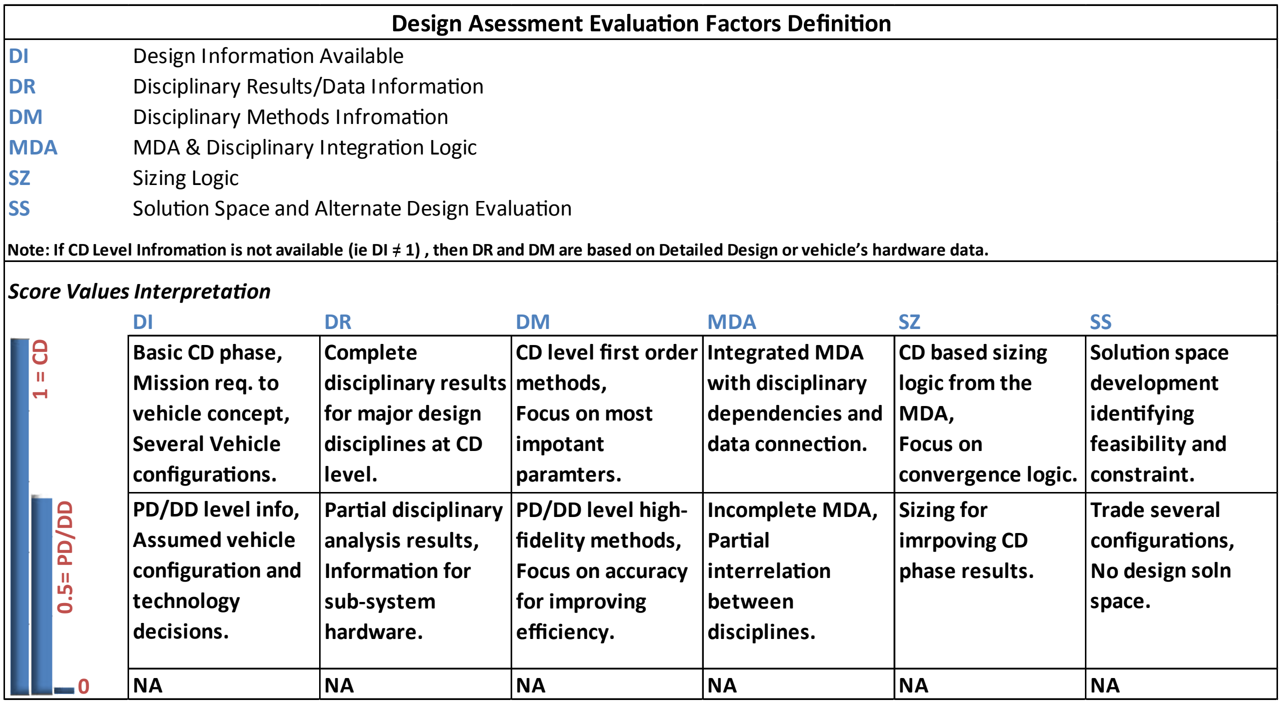
criteria for CD phase or DD/PD phase. Following scale identifies three levels specific to design phases:

» *Criteria Score = 0:* No information is found for a information criteria.

» *Criteria Score = 0.5:* Information found for the specific criteria is from the DD/PD phase or is related to the hardware for specific subsystem.

» *Criteria Score = 1:* Information found for the criteria is from the CD phase level assessment and provides insight on the major design decisions.

In this manner, the perfect case in terms of the CD specific information would be where all categories would receive a score of 1 in all information criteria. Figure 2.15 shows the interpretation of each information criteria for all three score levels. On this basis, the US based



**Design Asessment Evaluation Factors Definition**

| | |
|---|---|
| **DI** | Design Information Available |
| **DR** | Disciplinary Results/Data Information |
| **DM** | Disciplinary Methods Infromation |
| **MDA** | MDA & Disciplinary Integration Logic |
| **SZ** | Sizing Logic |
| **SS** | Solution Space and Alternate Design Evaluation |

**Note: If CD Level Infromation is not available (ie DI ≠ 1) , then DR and DM are based on Detailed Design or vehicle's hardware data.**

***Score Values Interpretation***

| | DI | DR | DM | MDA | SZ | SS |
|---|---|---|---|---|---|---|
| 1 = CD | Basic CD phase, Mission req. to vehicle concept, Several Vehicle configurations. | Complete disciplinary results for major design disciplines at CD level. | CD level first order methods, Focus on most impotant paramters. | Integrated MDA with disciplinary dependencies and data connection. | CD based sizing logic from the MDA, Focus on convergence logic. | Solution space development identifying feasibility and constraint. |
| 0.5= PD/DD | PD/DD level info, Assumed vehicle configuration and technology decisions. | Partial disciplinary analysis results, Information for sub-system hardware. | PD/DD level high-fidelity methods, Focus on accuracy for improving efficiency. | Incomplete MDA, Partial interrelation between disciplines. | Sizing for imrpoving CD phase results. | Trade several configurations, No design soln space. |
| 0 | NA | NA | NA | NA | NA | NA |

FIGURE 2.15 – Information criteria defined for assessment of CD level information available for each case-study. Perfect score = 1 is representative of comprehensive account of CD level information.

LRV programs were assessed scores for which are shown in Figure 2.16. As made clear from the assessment of the CD information criteria, the LRV case-studies show that this design phase is very poorly documented. The first criteria, DI is of special relevance as it primarily represents if any literature source is found that can be assigned specifically to the CD phase level assessment. Rest other criterias are then in turn look at particular information categories that represents characteristics of CD phase assessment. Disciplinary Results and Disciplinary Methods criteria can be found in substantial literature for the PD/DD phases but the last three criteria are significant to primarily for the CD phase and are found in very few sources.

Overall, this survey shows a design-weak nature of the information found for the case-studies reviewed. This is in contrast to the AHP survey results that finds a discipline-strong trend in most case-studies where individual disciplines are assessed for the influence and contribution to the hypersonic knowledge realm.

### 2.2.2 *Launch Vehicles (LV)*

Launch vehicles are the primary enablers for the space industry and have been in service ever since the launch of Sputnik in 1957. The size, capability and performance of the LVs since the first V-2 have grown significantly, where the mighty Saturn-V represents the most powerful

FIGURE 2.16 – CD assessment results for the US based case-studies.

launch capability with the capacity to reach the Moon, see Figure 2.17. But still, not much has changed on a fundamental design level. To this day, majority of the launch vehicles are operated on a one-time-use basis; a primary reason for the high costs of space launch economics. In this regards, reusability has become one of the most sought-after trait to achieve for the industry that could allow several magnitudes of reduction in SAS operations costs.

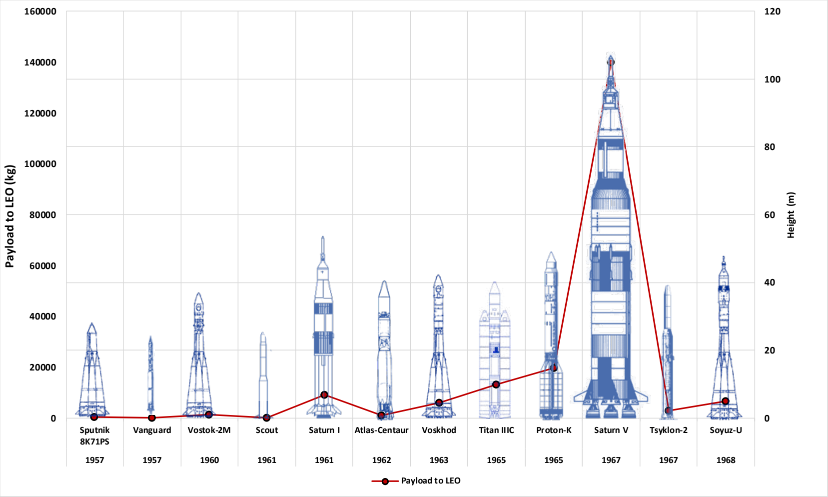


FIGURE 2.17 – Significant examples of LVs from the early days of the space industry.

Traditional users of the LV capability has primarily been the government agencies (USAF, NASA, Soviet Space Agencies etc) which contracted out the development and manufacturing of the product to the commercial industry partners (Lockheed, Martin Company, Boeing etc). Thus the LVs were developed explicitly for the governmnet purposes and consequently, the cost of operations was a government issue. This operational scenario changed in early 2000s when private companies like United Launch Alliance were allowed to operate the LV where the government agencies were paying customers and not the primary operators. This shift led to emergence of new players in the market in more recent times where a number of new companies are starting to address the launch capability in various capacity. NewSpace Ventures[47] is an online compendium of NewSpace products and companies which lists 600 plus companies from all over the globe in its database. The website shows currently 46 new companies address the Launch Vehicle market segment.[15] Startups like Vector, ARCA, REBEL Space,Rocket Lab and others are developing smaller scale LV capability that address mainly cube-sat and lower payload market segment.

With the current developments in the LV market, it is seen that that the commercial industry is now approaching the reusability and cost

[15] This does not include major established market players like ULA or SapceX but only new emerging companies.

reduction issues in a practical manner rather than focusing only on developing a fully reusable SSTO capability. SpaceX and Blue Origin are the major influence in this approach where both companies have already proven successful recovery of the first stage of a vertical launch vehicle. SpaceX in particular has recovered the first stage by vertically landing on a sea-barge or on land in 13 missions as of now, where two missions have flown previously recovered first stages.

### *Types of LV Considered*

Since with current state of the industry, several LV options are available and further improvements seems likely to result in a fully reusable system, this research study would thus focus on the execution of the primary sizing implementation for the LRV segment of the SAV while the LV segment would be selected as combination of pre-sized stages, as specified in Section 1.2.3. The primary reason for this approach is to keep the number of trade-studies for the SAS within the reasonable scope of a PhD research. Additionally, sizing the LRV stage using the application of the SAS-GDSP at hierarchy level-2 would also demonstrate the generic nature of solution implementation. To this effect, this section would only limit the discussion of the LVs to the SAV systems level and would not address LVs design disciplines. Thus, following discussion focuses on selection of the LV options possible by combination of individual stages and not by the subsystem disciplines like propulsion, stability etc. like done for the LRVs in previous section.

There are several ways to categorize launch vehicles, usually based on payload capacity or the number of stages. In this research study, the classification scheme applied is based on the level of reusability of the vertical LVs. The main reason to follow this approach is to address the near-term availability of the LVs considering currently existing technology. Following three type of vertical LVs are thus identified:

1. *Expendable Launch Vehicle (ELV):* Most common and prevalent category. Eg. ULA Atlas-V.

2. *Partially Reusable Launch Vehicle (PRLV):* Currently operational and in-development vehicles that can recover atleast first stage of a multistage LV. Eg. SpaceX Falcon 9.

3. *Fully Reusable Launch Vehicle (FRLV):* An extrapolation of current PRLVs based on assumption of a recoverable second stage or using just the first stage of PRLVs to boost a LRV stage to orbit.

In addition to the examples given for each category, several other configurations can be extrapolated by addition of solid-rocket boosters with the first stage or an external expandable fuel tank attached to the

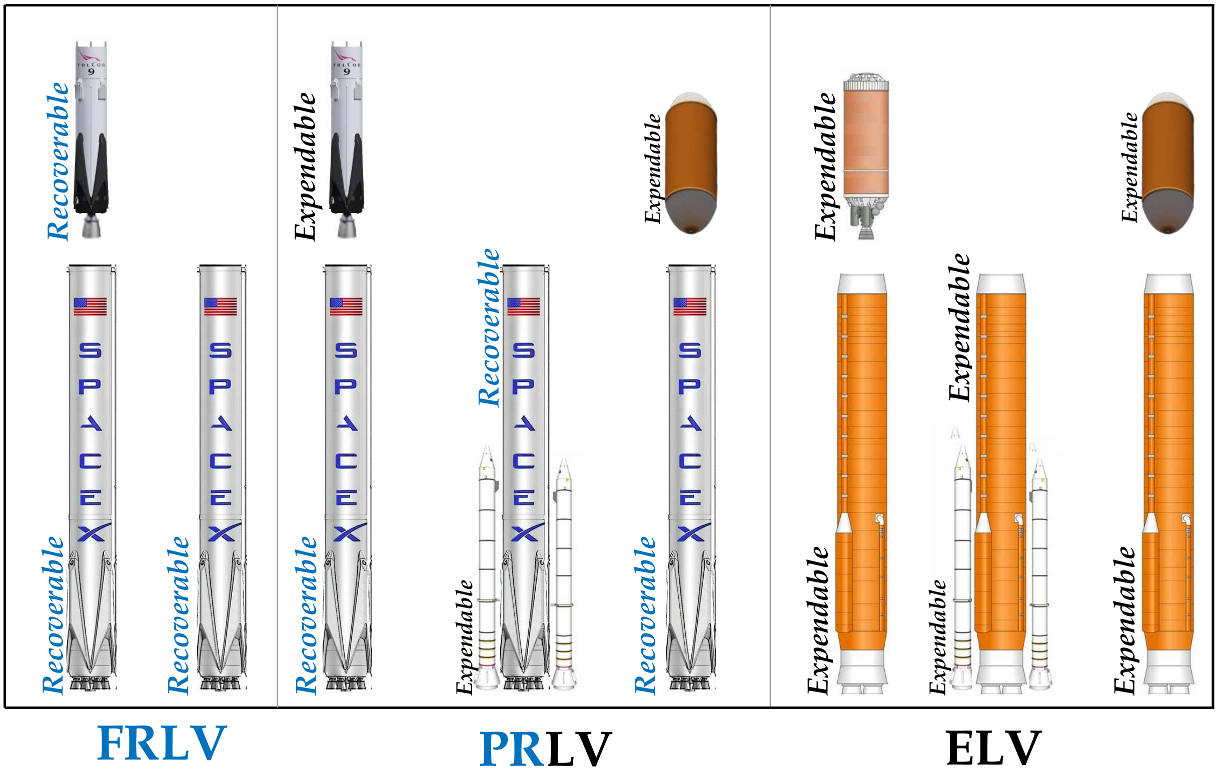


FIGURE 2.18 – Types of LV considered as various combination of constituent stages.

LRV in place of the second stage of the LV. These scenarios are shown in Figure 2.18.

*LVs in the TSTO-VTHL*

Considering the case for the VTHL-SAS configuration, the role of the LV is to boost the horizontal landing reentry stage to the orbit. In this regard, the reentry vehicle acts as a payload for the launch vehicle, which impose further constraints for the SAS configuration. Moss and Dorrington[48] recognize this system's effect as follow:

> Whilst spacecraft design alone introduces considerable technical challenge, the technology involved in the launch will often amplify the complexityâĂŤimposing many additional mission and design constraints...Of particular concern to the user, in relation to spacecraft design, are the constraints that the launcher imposes on the mission. These arise especially in terms of payload mass and size, but also include the selection of launch sites and launch windows, the launch environment as well as issues of safety and reliability.

These constraints are used while matching the sized LRV concepts with the options recognized for the LV options. In this manner, a SAS concept is assembled where several trade options are feasible. The

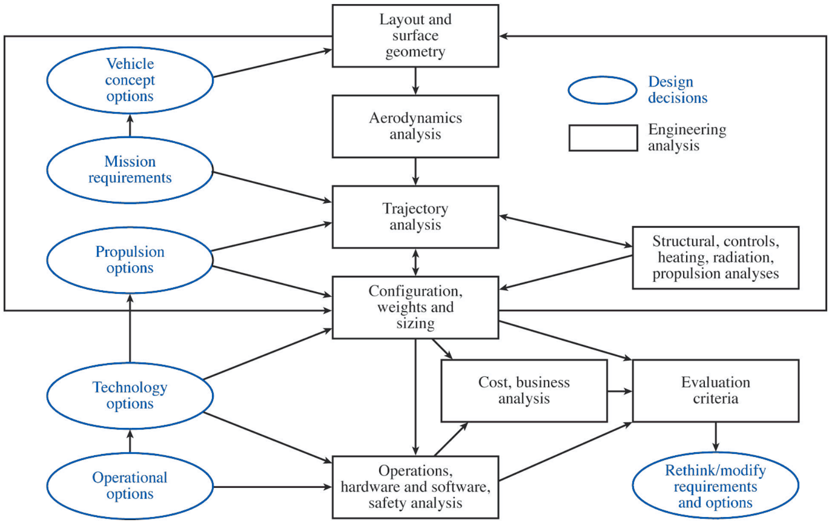


FIGURE 2.19 – Launch vehicle design process. The decisions taken at this stage decide the success or failure of a project. Reproduced from Rowell and Korte[49]

SAS-GDSP would then assess all feasible SAS options to select the most optimum design point.

This marks the end of the review and discussion of the VTHL case-study. Following is the review of the design synthesis methodologies used in the conceptual design phase.

## 2.3 *Review of Design Synthesis Methodologies*

An aerospace vehicle design synthesis process[16] is a systematic way to conceptually design the complex vehicle systems by considering the interdisciplinary integration among primary design disciplines. Generally, a synthesis approach includes a set of analysis methods for main design disciplines and a synthesis process logic to integrate the methods in a cohesive simulated environment, thus providing conceptual design of a flight vehicle system. Figure 2.19 from a NASA technical memorandum report by Rowell and Korte[49] shows the launch vehicle conceptual design process, highlights how the the design decisions taken during the CD phase decides the technological and operational aspects of the vehicle. These decisions influence the final success or failure of the product and must be forecasted based on informed decision making. Clearly, this capability is most desired by the chief decision maker.

Although, majority of flight vehicle design synthesis approaches are primarily oriented towards aircraft design, the multi-disciplinary integration logic can be applied to the SAS design by specifying the conditions and constraints applicable for the space environment. Coley[50] observes certain parallels between aircraft and spacecraft domain which

*Synthesis*
a: the composition or combination of parts or elements so as to form a whole
b: the combining of often diverse conceptions into a coherent whole; also: the complex so formed
- Merriam-Webster

[16] Legacy synthesis approaches are manual or handbook type approach and are referred as *Synthesis Methodologies* while Modern synthesis approaches are computerized programs and referred as *Synthesis Systems*

serve to highlight the similarity in design fundamentals, see Figure 2.20.

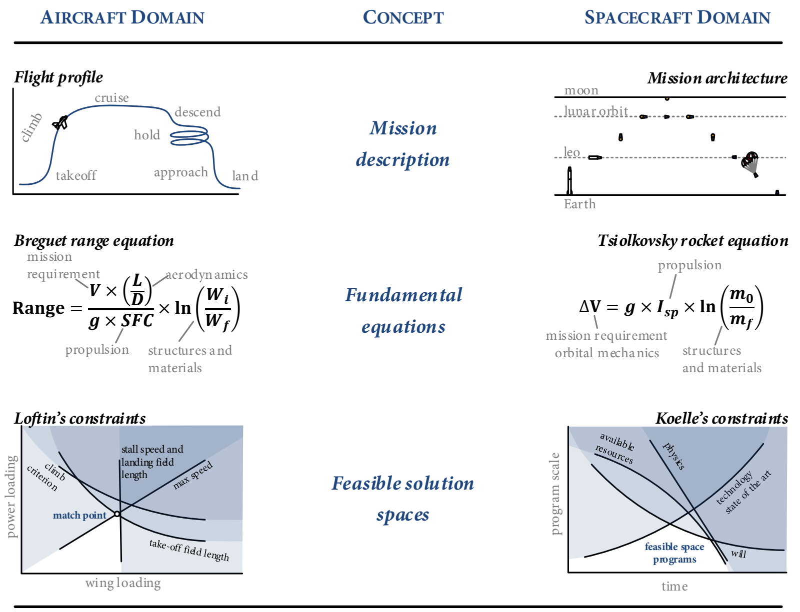


FIGURE 2.20 – Comparisons between the aircraft and spacecraft domains show parallels observed between the aircraft domain and the spacecraft domain by Coley[50].

The history of aircraft design philosophy could be traced back all the way to 1809 when Sir George Cayley[51] first proposed an aircraft design archetype. Also known as Cayley's Design Paradigm, it states that all design functions like aerodynamics, propulsion, stability & control et al are distributed distinctly over different hardware and subsystems. Based on this philosophy, conventional subsonic aircrafts have been designed to this day by first optimizing individual hardware for its own functions and then integrating them together in one flight vehicle system. Cayle's design paradigm assumes that the subsystems are decoupled with weak interconnections among them. Contrary to this assumption, a hypersonic flight vehicle is a fully integrated system (due to the constraints imposed by the extremely harsh operating environment) where the integrated system performs all the required functions, Figure 2.21. Clearly, a hypersonic vehicle design shows significant interdependence between constituent subsystems where one subsystem could have significant affect on the overall system design.

The Aerospace Vehicle Design (AVD) Laboratory is an exotic and unique research environment that primarily focuses on advancing the state of the art in conceptual design practices of flight vehicle systems. Through cumulative and continuing research efforts of several generations of researchers, AVD has been expanding and developing an expansive library of valuable data and knowledge, applicable to conceptual design synthesis. Several AVD members (Chudoba, Huang, Coleman, Gonzalez, Omoragbon, Oza et al) in the past have studied and reviewed the legacy and modern synthesis methodologies in great details. Author finds it more effective to leverage the work of previous AVD members which entails the synopsis and key features of 126 unique synthesis systems developed over the last 50 years, rather than reviewing every system on his own. To this effect, the next section addresses classical synthesis methodologies and modern synthesis systems to identify the requirement specifications for SAS-GDSP.

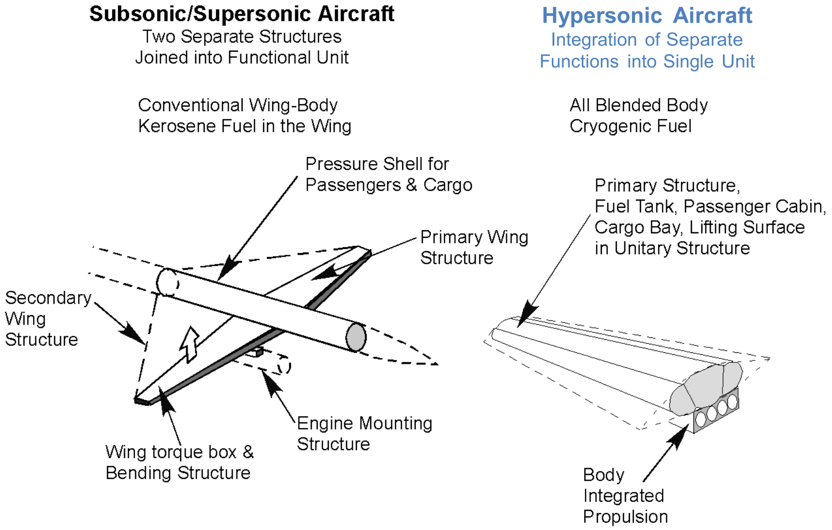


FIGURE 2.21 – Hypersonic Vehicle is a fully integrated system unlike Subsonic/Supersonic Vehicles. The coupling interconnection between elements is high due to extreme operating conditions. Reproduced from Czysz[52]

» *Synthesis Systems Evolution(Chudoba)[9]*: Chudoba provides a historical review of the flight vehicle design synthesis systems and tracks the evolution in design approaches. A hierarchy of five generations of synthesis systems is developed, based on increasing proficiency at integrating multi-disciplinary effects, see Table 2.3."The classification scheme selected distinguishes the multitude of vehicle analysis and synthesis approaches according to their modeling complexity, thereby expressing their limitations and potential."[25]

The first four generations of synthesis systems address chronological and modeling-complexity evolution of design approaches from year 1905 to present day capability, highlighting primary characteristics of each class. This includes classical design approaches developed primarily towards aircraft sizing.

The transition from Class II to Class III represents first use of computer automation in the design environment. These early design methodologies are found to focus on the selected discipline-specific analysis but lack the multidisciplinary integration that is later implemented manually. Lovell comments, *"initial computer applications were confined to aspects of structural analysis and wing design. There was some resis-*

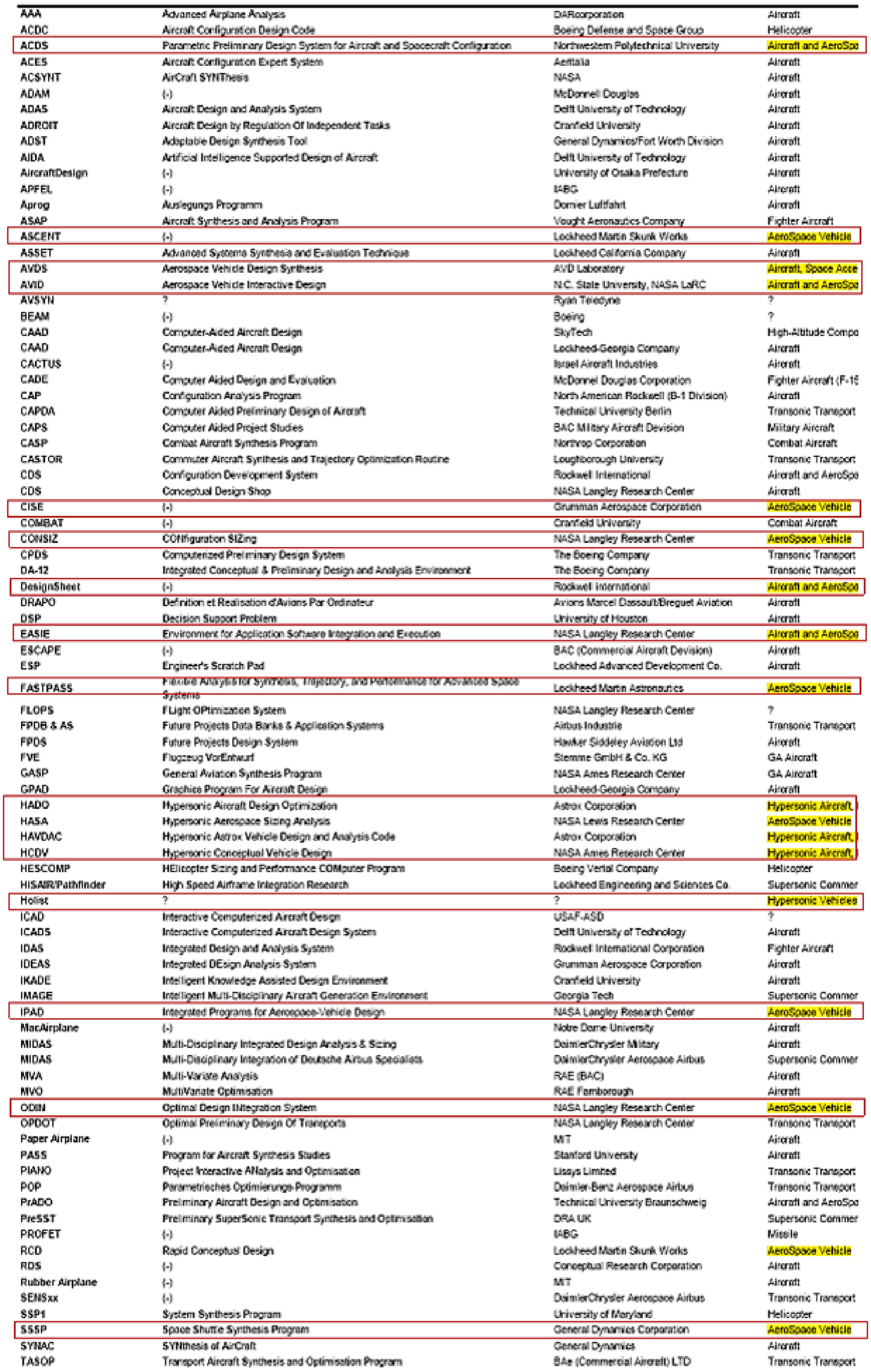
| **Class** | **Design Definition** | **Develop Time** | **Characteristics** |
|---|---|---|---|
| Class I | Early Dawn | Until 1905 | Trial and error approach, experiment, no systematic methodology |
| Class II | Manual Design Sequence | 1905-1955 | Physical design transparency, parameter studies, standard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

TABLE 2.3 – Classification of aerospace design synthesis approaches by Chudoba[25]

*tance to the use of computers in initial project design because of the complex decision-making process involved. However, they enabled more detailed analyses to be made and hence allowed a greater range of carpet plots with additional overlays to be prepared to show the effects of configuration variables on performance [53]"*

Class IV synthesis systems are identified to involve multidisciplinary integration with the disciplinary analysis, but are limited in application to a single-point design optimization and mostly applicable to one specific vehicle configuration. Majority of synthesis systems upto Class IV are applicable only for subsonic aircrafts while only selected few address Space Access Vehicles. Synthesis systems like CzyszâĂŹ Hypersonic Convergence[52] and PrADO Hy.[8] are identified as significant methodology implementations from Class IV type systems. The assessment leads Chudoba to define the requirements for a Class V - Generic Synthesis Capability, which is identified as a *design process rather than a design tool*. In this regards, the focus here is on developing the capability over its application. The primary emphasis in this class is on the application of a modular and dedicated disciplinary methods libraries for integration of multi-disciplinary effects. Table 2.4 provides the list of class IV design approaches reviewed by Chudoba, where highlighted approaches provide partial synthesis capability towards SAS.

As mentioned in Chapter 1, current dissertation focuses on development of a Class V synthesis capability. The main specification for SAS-GDSP identified from this review is that the primary emphasis for developing the SAS-GDSP must be on the underlying process, strategy and logic of the the capability to enable identification of feasible design solution space.



| | | | |
|---|---|---|---|
| AAA | Advanced Airplane Analysis | DARcorporation | Aircraft |
| ACDC | Aircraft Configuration Design Code | Boeing Defense and Space Group | Helicopter |
| ACDS | Parametric Preliminary Design System for Aircraft and Spacecraft Configuration | Northwestern Polytechnical University | Aircraft and AeroSpa |
| ACES | Aircraft Configuration Expert System | Aeritalia | Aircraft |
| ACSYNT | AirCraft SYNThesis | NASA | Aircraft |
| ADAM | (-) | McDonnell Douglas | Aircraft |
| ADAS | Aircraft Design and Analysis System | Delft University of Technology | Aircraft |
| ADROIT | Aircraft Design by Regulation Of Independent Tasks | Cranfield University | Aircraft |
| ADST | Adaptable Design Synthesis Tool | General Dynamics/Fort Worth Division | Aircraft |
| AIDA | Artificial Intelligence Supported Design of Aircraft | Delft University of Technology | Aircraft |
| AircraftDesign | (-) | University of Osaka Prefecture | Aircraft |
| APFEL | (-) | IABG | Aircraft |
| Aprog | Auslegungs Programm | Dornier Luftfahrt | Aircraft |
| ASAP | Aircraft Synthesis and Analysis Program | Vought Aeronautics Company | Fighter Aircraft |
| ASCENT | (-) | Lockheed Martin Skunk Works | AeroSpace Vehicle |
| ASSET | Advanced Systems Synthesis and Evaluation Technique | Lockheed California Company | Aircraft |
| AVDS | Aerospace Vehicle Design Synthesis | AVD Laboratory | Aircraft, Space Acce |
| AVID | Aerospace Vehicle Interactive Design | N.C. State University, NASA LaRC | Aircraft and AeroSpa |
| AVSYN | ? | Ryan Teledyne | ? |
| BEAM | (-) | Boeing | ? |
| CAAD | Computer-Aided Aircraft Design | SkyTech | High-Altitude Compo |
| CAAD | Computer-Aided Aircraft Design | Lockheed-Georgia Company | Aircraft |
| CACTUS | (-) | Israel Aircraft Industries | Aircraft |
| CADE | Computer Aided Design and Evaluation | McDonnel Douglas Corporation | Fighter Aircraft (F-1 |
| CAP | Configuration Analysis Program | North American Rockwell (B-1 Division) | Aircraft |
| CAPDA | Computer Aided Preliminary Design of Aircraft | Technical University Berlin | Transonic Transport |
| CAPS | Computer Aided Project Studies | BAC Military Aircraft Devision | Military Aircraft |
| CASP | Combat Aircraft Synthesis Program | Northrop Corporation | Combat Aircraft |
| CASTOR | Commuter Aircraft Synthesis and Trajectory Optimization Routine | Loughborough University | Transonic Transport |
| CDS | Configuration Development System | Rockwell International | Aircraft and AeroSpa |
| CDS | Conceptual Design Shop | NASA Langley Research Center | Aircraft |
| CISE | (-) | Grumman Aerospace Corporation | AeroSpace Vehicle |
| COMBAT | (-) | Cranfield University | Combat Aircraft |
| CONSIZ | CONfiguration SIZing | NASA Langley Research Center | AeroSpace Vehicle |
| CPDS | Computerized Preliminary Design System | The Boeing Company | Transonic Transport |
| DA-12 | Integrated Conceptual & Preliminary Design and Analysis Environment | The Boeing Company | Transonic Transport |
| DesignSheet | (-) | Rockwell International | Aircraft and AeroSpa |
| DRAPO | Definition et Realisation d'Avions Par Ordinateur | Avions Marcel Dassault/Breguet Aviation | Aircraft |
| DSP | Decision Support Problem | University of Houston | Aircraft |
| EASIE | Environment for Application Software Integration and Execution | NASA Langley Research Center | Aircraft and AeroSpa |
| ESCAPE | (-) | BAC (Commercial Aircraft Devision) | Aircraft |
| ESP | Engineer's Scratch Pad | Lockheed Advanced Development Co. | Aircraft |
| FASTPASS | Flexible Analysis for Synthesis, Trajectory, and Performance for Advanced Space Systems | Lockheed Martin Astronautics | AeroSpace Vehicle |
| FLOPS | FLight OPtimization System | NASA Langley Research Center | ? |
| FPDB & AS | Future Projects Data Banks & Application Systems | Airbus Industrie | Transonic Transport |
| FPDS | Future Projects Design System | Hawker Siddeley Aviation Ltd | Aircraft |
| FVE | Flugzeug VorEntwurf | Stemme GmbH & Co. KG | GA Aircraft |
| GASP | General Aviation Synthesis Program | NASA Ames Research Center | GA Aircraft |
| GPAD | Graphics Program For Aircraft Design | Lockheed-Georgia Company | Aircraft |
| HADO | Hypersonic Aircraft Design Optimization | Astrox Corporation | Hypersonic Aircraft, |
| HASA | Hypersonic Aerospace Sizing Analysis | NASA Lewis Research Center | AeroSpace Vehicle |
| HAVDAC | Hypersonic Astrox Vehicle Design and Analysis Code | Astrox Corporation | Hypersonic Aircraft, |
| HCDV | Hypersonic Conceptual Vehicle Design | NASA Ames Research Center | Hypersonic Aircraft, |
| HESCOMP | HElicopter Sizing and Performance COMputer Program | Boeing Vertol Company | Helicopter |
| HISAIR/Pathfinder | High Speed Airframe Integration Research | Lockheed Engineering and Sciences Co. | Supersonic Commer |
| Holist | ? | ? | Hypersonic Vehicles |
| ICAD | Interactive Computerized Aircraft Design | USAF-ASD | ? |
| ICADS | Interactive Computerized Aircraft Design System | Delft University of Technology | Aircraft |
| IDAS | Integrated Design and Analysis System | Rockwell International Corporation | Fighter Aircraft |
| IDEAS | Integrated DEsign Analysis System | Grumman Aerospace Corporation | Aircraft |
| IKADE | Intelligent Knowledge Assisted Design Environment | Cranfield University | Aircraft |
| IMAGE | Intelligent Multi-Disciplinary Aircraft Generation Environment | Georgia Tech | Supersonic Commer |
| IPAD | Integrated Programs for Aerospace-Vehicle Design | NASA Langley Research Center | AeroSpace Vehicle |
| MacAirplane | (-) | Notre Dame University | Aircraft |
| MIDAS | Multi-Disciplinary Integrated Design Analysis & Sizing | DaimlerChrysler Military | Aircraft |
| MIDAS | Multi-Disciplinary Integration of Deutsche Airbus Specialists | DaimlerChrysler Aerospace Airbus | Supersonic Commer |
| MVA | Multi-Variate Analysis | RAE (BAC) | Aircraft |
| MVO | MultiVariate Optimisation | RAE Farnborough | Aircraft |
| ODIN | Optimal Design INtegration System | NASA Langley Research Center | AeroSpace Vehicle |
| OPDOT | Optimal Preliminary Design Of Transports | NASA Langley Research Center | Transonic Transport |
| Paper Airplane | (-) | MIT | Aircraft |
| PASS | Program for Aircraft Synthesis Studies | Stanford University | Aircraft |
| PIANO | Project Interactive ANalysis and Optimisation | Lissys Limited | Transonic Transport |
| POP | Parametrisches Optimierungs-Programm | Daimler-Benz Aerospace Airbus | Transonic Transport |
| PrADO | Preliminary Aircraft Design and Optimisation | Technical University Braunschweig | Aircraft and AeroSpa |
| PreSST | Preliminary SuperSonic Transport Synthesis and Optimisation | DRA UK | Supersonic Commer |
| PROFET | (-) | IABG | Missile |
| RCD | Rapid Conceptual Design | Lockheed Martin Skunk Works | AeroSpace Vehicle |
| RDS | (-) | Conceptual Research Corporation | Aircraft |
| Rubber Airplane | (-) | MIT | Aircraft |
| SENSxx | (-) | DaimlerChrysler Aerospace Airbus | Transonic Transport |
| SSP1 | System Synthesis Program | University of Maryland | Helicopter |
| SSSP | Space Shuttle Synthesis Program | General Dynamics Corporation | AeroSpace Vehicle |
| SYNAC | SYNthesis of AirCraft | General Dynamics | Aircraft |
| TASOP | Transport Aircraft Synthesis and Optimisation Program | BAe (Commercial Aircraft) LTD | Transonic Transport |

TABLE 2.4 – Class IV design synthesis systems. Highlighted systems show partial applicability towards VTHL SAS

*SAV Synthesis Systems Review(Huang)* [7]

Huang expands on Chudoba's synthesis systems review with an in-depth assessment of 115 aircraft, helicopter, missile, and launch vehicle design synthesis methodologies. This comprehensive review assesses the overview of the development history, design logic, module evaluation, and software development description of synthesis methodologies, concluding with the advantages and disadvantages of every methodology. Huang notes that only a few synthesis systems are applicable for SAVs, identifying selected non-integrated or manual SAV design methodologies[17] and computer-based synthesis systems[18]. Huang lists these top-level inferences from the assessment, defining the then state of the art(circa 2004):

- *Design synthesis systems are the heart of aerospace vehicle design organizations (Boeing, Lockheed Martin, Airbus, etc). The development of a synthesis system is a demanding task and requires large research activities.*
- *Most of the synthesis systems are developed for aircraft design. Very few SAV design synthesis systems exist. Especially, there is a lack of efficient design synthesis systems for highly integrated SAV-type vehicles because the Cayley's design paradigm is no longer valid.*
- *Synthesis is the key to close (converge) the design through iterations. Major synthesis systems estimate design sensitivities and support optimizing flight vehicle configurations, but only a few synthesis systems are capable of delivering a proof of convergence. The main drawback of current synthesis systems, especially for SAVs, is that they are not able to efficiently define the design space and prove design convergence.*
- *Many design synthesis systems tend to have a common structure with different computational procedures. However, the design methodologies of synthesis systems are not transparent. There is a lack of efficient computerized synthesis systems and multi-disciplinary interaction at the conceptual design level.*
- *Current design synthesis systems tend to develop a new system for each new application. There is no generic synthesis system for the SAV conceptual design.*
- *Some systems utilize design statistics (PIANO, AAA) but lack having available a dedicated CD-Knowledge-Based System for SAV design.*
- *Managerial decision-making power using a synthesis system is often underestimated and not understood.*

The review identifies common characteristic traits of synthesis systems [19] and highlights the inability of existing methodologies in comprehensively addressing each trait. Huang notes, "The survey clearly

[17] *Significant Manual SAV synthesis methodologies reviewed by Huang:*
K.D. Wood[54] P. Czysz[52], W.E. Hammond[2], J.L. Hunt[55]

[18] *Computer-based SAV synthesis systems reviewed by Huang:*
PrADO-Hy[8], SSSP[56]

[19] Mathematical Modeling, Multidisciplinary Analysis and Optimization, Knowledge-Based System, and Generic Concepts

shows that the current conceptual design capabilities available for the design of SAVs are design method and software limited rather than computer limited." This conclusion led Huang to define following standards that a Class-V synthesis system must be capable to adopt:

1. Generic Design Capability
2. Multi-Disciplinary Design Capability
3. Dedicated SAV Conceptual Design Knowledge-Based System (SAV CD-KBS)
4. Multi-Disciplinary Design Optimization (MDO)
5. Database Management System (DMS)

Based on these specifications, Huang developed a synthesis methodology for a sub-orbital case-study (a HTHL-SAV; OU-XP) to demonstrate the solution concept feasibility. Huang's solution proposes to divide the overall mission profile into several sub-sections and synthesizes the vehicle for each mission phase. Following this, the final step assembles the vehicle for the complete mission profile. Huang also employs a cost analysis for the case-study for a sub-orbital tourism based scenario.

The key insight from Huang's review following the standards specification for Class-V synthesis system is the inclusion of a Knowledge-Based System and Database Management System in the conceptual design synthesis application. These specialized systems expand the capability of synthesis systems to control utilization of parametric data and design methods within a multi-disciplinary framework. This capability allows the expansion of the synthesis system's applicability scope in addition to the disciplinary methods.

» *Aircraft Conceptual Design Methodologies Review(Coleman)*: Coleman[27] in continuation of Chudoba and Huang, surveys aircraft design synthesis systems applicable at conceptual design. He divides the aircraft conceptual design phase in three distinct chronological steps, (1) Parametric sizing, (2) Configuration Layout, and (3) Configuration Evaluation. Coleman recognizes parametric sizing as the vital first step where disciplinary technology and vehicle configuration are combined using a multi-disciplinary framework to provide first feasibility assessment of vehicle's size and scale. He defines sizing process composed of six fundamental elements[20] and identifies two major categories of sizing processes. Following this, Coleman provides details of logic, application and interpretation of 11 manual[21] and, 7 computerized[22] sizing processes in a process library, complemented by Nassi-Shneiderman(NS) structograms representation for each synthesis system. In addition to process library, Coleman also developed

[20] see section 3.1

[21] *Manual sizing processes reviewed by Coleman:*
Wood[57], Corning[58], Nicolai[59], Loftin[60], Tornbeek[61], Stinton[62], Roskam[63], Raymer[64], Jenkinson[65], Howe[66], and Schaufele[67]

[22] *Computerized sizing processes reviewed by Coleman:*
AAA[63], ACES [68], ACSYNT[69], ASAP[70], FLOPS[71], PrADO[8] and Hypersonic Convergence[52]

a methods library consisting of disciplinary methods found as either parts of a synthesis system, or as standalone analytic methods found in literature.

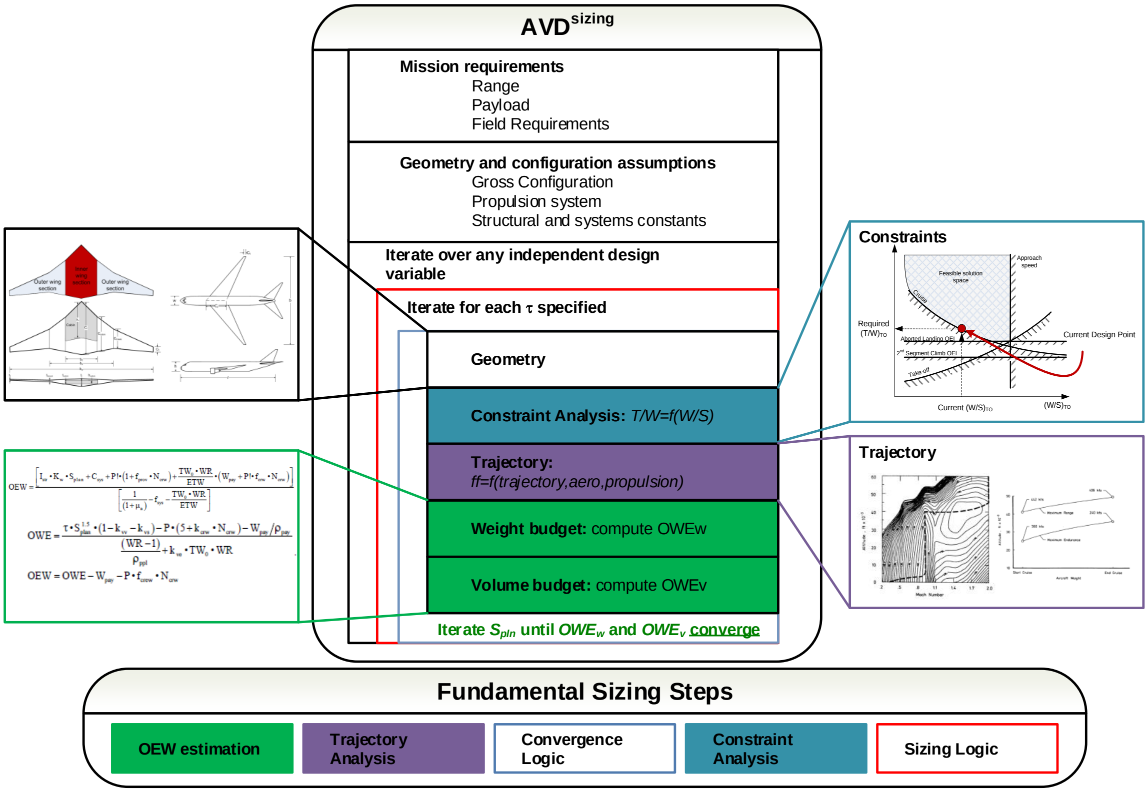


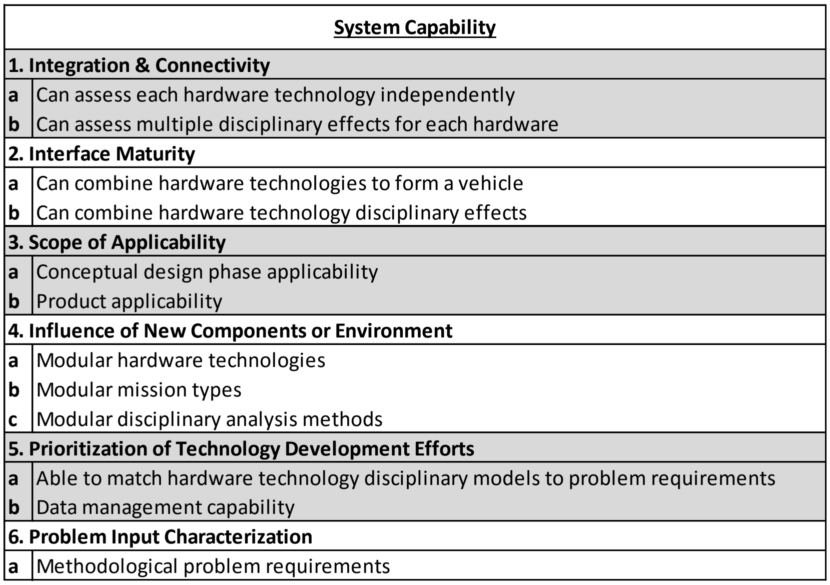
FIGURE 2.22 – Fundamental AVD$^{Sizing}$ logic based on Paul Czysz's Hypersonic Convergence[52] methodology. Reproduced from Coleman[27].

Coleman applies the results from the review to define the AVD$^{Sizing}$ (AVDS) logic based on the methodology of Paul Czysz's Hypersonic Convergence[52], see Figure 2.22. Coleman comments, *"Most sizing processes, converge weight only (i.e. compute the fuel and empty weight for a given trajectory), then volume is checked as an inequality constraint...by using volume as equality constraint instead of an inequality constraint the sizing problem can be reduced to fewer fundamental design variables. Numerically, the reduction of one design variables (via 1 additional equation, volume) is not significant. However, for design space visualization this technique has proven useful for increasing the physical understanding of the design space for both unconventional and conventional aircraft....Formulated in this manner, the fundamental process is applicable to any fixed wing aircraft or launcher with changes in the disciplinary methods and geometry module when appropriate."*

Coleman then applies the AVD$^{Sizing}$ logic in a computerized MDA synthesis system referred as AVDS, that is composed of a MATLAB based modular structure where the disciplinary methods are independent MATLAB files combined in a systematic MDA. A wide spectrum of conventional and unconventional transonic aircrafts and hypersonic cruise vehicles case-studies are executed to demonstrate the generic application of the system.

The main finding of the review remains that parametric sizing aspect of conceptual design synthesis is stagnated and ignored in the current literature. The key specification for SAS-GDPS recognized from this review is that a synthesis capability must have distinct systems for handling disciplinary methods and integration processes that are utilized in execution of the parametric sizing. Combined with Huang's specifications, it becomes apparent that a Database Management System would be the ideal choice to manage these libraries.

» *Survey of Synthesis Systems in terms of System Capability (Gonzalez, Omoragbon and Oza)*: Gonzalez[26], Omoragbon[72] and Oza[11] review 11 By-Hand synthesis methodologies[23] and 9 Computer-Based synthesis systems[24] based on the system capability criteria. The review criteria measures the "capability of synthesis systems to characterize, analyze, and solve classical and new/novel aerospace problems" and is broken into six categories shown in Figure 2.23. The review assesses the selected synthesis systems for each category and identifies the need for a database management system (DBMS) in aerospace synthesis as a significant requirement. Following this crucial capability identification, the Computer-Based synthesis systems are reviewed to assess



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

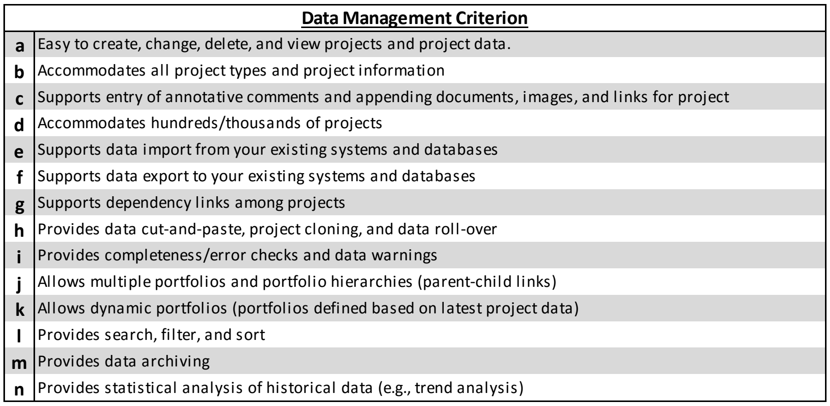
FIGURE 2.23 – System capability criteria used by Gonzalez, Oza and Omoragbon to assess the current state of the art synthesis system capability. Reproduced from Gonzalez[26].

[23] *By-Hand synthesis methodologies reviewed by Gonzalez, Oza, Omoragbon:* Wood[57], Corning[58], Nicolai[59], Loftin[60], Tornbeek[61], Stinton[62], Roskam[63], Raymer[64], Jenkinson[65], Howe[66], and Schaufele[67]

[24] *Computer-Based synthesis systems reviewed by Gonzalez, Oza, Omoragbon:* AAA[63], ACSYNT[69], FLOPS[71], PrADO[8], Hypersonic Convergence[52], AVDS[27], pyOPT[73] and Model Center

their capability to address the DBMS implementation. This is done by defining additional list of data management criteria shown in Figure 2.24. Model Center and pyOPT are shown to have the highest degree of data management capability as Gonzalez notes, “The database management system in each case has been designed not to connect pieces to solve a specific problem, but instead to connect pieces to solve a user-defined problem." This aspect is identified missing in classical aircraft synthesis systems and is proposed as the highlight capability to be introduced in the next generation of the synthesis systems.

The final conclusion from the review is stated as follows, *“One of the major takeaways has been that the systems able to model the widest variety of problems have a database management system that is able to adapt its structure for a given problem, Model Center as the prime example. The open and adaptable nature of integration frameworks like Model Center while allowing for easy connection between new and legacy tools, do not have any structure or format for analysis in and of themselves. They are created with the requirement that a synthesis specialist knows from the outset what he wants to model, how he wants to model it, and how everything should be connected. This means that while data connections can be easily made between analysis modules, the question of which modules to choose for a given problem is still solely a function of user experience[26].”*



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

FIGURE 2.24 – Data Management criterion assesses the capability of Computer-Based synthesis systems to manage and transfer data within the system. Reproduced from Gonzalez[26].

The review leads to specification for creation of a system that approaches aircraft synthesis from a data management approach similar to Model Center. The system in reference was created as a collaborative effort among three researchers at the AVD lab and is referred as the AVD$^{DBMS}$ (also referred to as simply the DBMS). The DBMS is not a design synthesis, instead it is a prototype implementation that provides the unique capability of developing custom tailor synthesis systems specific to the problem. The software is executed in MS-ACCESS using the VBA and SQL programming language and acts as a warehouse of the modules that are the basic building blocks of a synthesis MDA. The user selects problem specific components from this warehouse-type setting and combines them together by following a systematic step by step process to create unique synthesis MDA based on problem specific demands. The DBMS implementation demonstrates a fundamental paradigm shift in the way traditional design has been approached till now and is recognized as a Class V synthesis capability for the flight vehicle synthesis systems.

The DBMS was applied to demonstrate the aforementioned unique capability as a part of the AFRL Summer Faculty Fellowship Program by Chudoba and Gozalez[74]. An AFRL initiative, the generic hypersonic vehicle (GHV) study was used as the verification case-study to validate the results of the DBMS by Gonzalez. The DBMS results showed general agreement with the GHV reference data. System's potential was recognized by the USAF as the Fellowship Program extended to a research contract with AVD LLC., where the system was further applied for the follow-up phases of the GHV study[74]. The DBMS development process, GHV verification results and further details of the system are found in the PhD dissertations of Gonzalez[26], Omoragbon[72] and Oza[11].

The primary take-away from this review is the significance of the data management application in a Class V synthesis capability and the significance of the application of a system with the functional features like that of the AVD$^{DBMS}$

» *Synthesis systems review synopsis and lessons learned*: The reviews by Chudoba, Huang, Coleman, Gonzalez, Omoragbon and Oza provide a comprehensive account of the evolution and current state of the art of the flight vehicle synthesis capabilities, covering a total of 126 synthesis approaches. The reviews also act as an accelerating platform to gain the fundamental understanding of the synthesis systems and their applications in the aircraft and the SAS domain. Following discussion provides an overview synopsis of the reviews discussed above:

1. A Class V synthesis capability is distinctly identified as representative of the current state of the art. The primary aim while developing a Class V synthesis capability is on the underlying development process, strategy and logic of the capability. Further, the Class V synthesis capability must be generic in logic and be applicable to a wide array of flight vehicle configurations, rather than one specific class. Thus, a Class V SAS synthesis capability must be applicable to the four primary categories defined in Section 1.1.1 in Chapter 1.

2. A state of the art Class V synthesis capability must be able to generate and screen a comprehensive design solution space for the CD

phase, consisting of design concepts satisfying the required mission objectives. A design solution space is developed through the trades conducted for the primary design drivers that constitute the product being designed. Clearly, this requires that the Class V capability for the SAS must be able to execute trades for elements at hierarchy level-2 and level-3, and further define consistent comparative criteria to access the design solution for the technical and business-case feasibility.

3. In order to address the information-scarce nature of the CD phase, a Data-Base system is identified as a crucial requirement for the Class V synthesis systems. The Data-Base system is defined as a proficient toolbox to catalog and store the information specific to the past projects, vehicles and primary design disciplines. This information aids designer to make informed approximations and assumptions for the multi-disciplinary framework execution, and to define practical trade studies. For the SAS domain, the Data-Base system must address elements belonging to hierarchy level-2 (the SAVs) and hierarchy level-3.

4. Parametric sizing is recognized as the vital system capability that is implemented in a mathematical framework to integrate the disciplinary methods in a multi-disciplinary process and implement a convergence criteria to size the design concepts. In this aspect, distinct systems are required to manage a library of discipline-specific analysis methods and the multi-disciplinary integration processes.

5. A Data Management System is shown to be a crucial capability that enables a Class V synthesis system to model the widest variety of problems. This capability regulates the flow of information within the parametric sizing execution, controls data transfer between involved disciplinary modules and implements utilization of disciplinary methods in the multi-disciplinary framework. A robust data management system is found missing in the flight vehicle synthesis approach and has been applied in the AVD$^{DBMS}$ to develop a prototype Class V synthesis system that for the first time enables the designer to create tailor-made customized synthesis systems based on project requirements.

## 2.4 *Research Hypothesis Justification and System Specification*

Based on the understanding gained from the comprehensive reviews of the selected case-study and the research application domain, this section specifies where and how this current research study contributes to advancing the state of the art of the CD domain. This is addressed in the first part and serves as the justification for the research hypothesis presented in Chapter 1, section 1.2.3. The second part then provides the specification for the SAS-GDSP solution, which also serves as the main objectives of the research.

### 2.4.1 *Commentary on the current CD capabilities and the Scope to make an original research contribution:*

The review of the existing synthesis capabilities provides an understanding of the current state of the art and the scope of the existing capabilities for the CD phase. The following discussion then recognizes where and how this scope can be expanded, specific to the domain of the SAS. This also serves as the justification of the primary research hypothesis and specifically identifies the novel original contributions of this dissertation to the field of aerospace design in general and the multi-disciplinary sciences in specific.

The following traits have been identified

1. Majority of the existing synthesis systems are limited to the aircraft domain while only very few synthesis approaches are available for Space Access Vehicles. This is found true for the selected SAV class, LRV systems, as shown through the comprehensive assessment of the past LRV programs conducted in Section 2.2.1 where no comprehensive CD phase documentation is found for the 60 LRV projects assessed.

2. Most synthesis approaches are found to belong to the Class IV category and address a specific configuration. Hypersonic Convergence, AVDS and DBMS are notable exceptional Class V capabilities which do address a wide range of configurations and represents the incremental development in the capability to address CD phase more comprehensively to support the decision maker in forecasting correct trends and foresee avoidable mistakes. The AVDS systems has been built on the fundamental logic of the Hypersonic Convergence's generic design approach and improved on the capability to produce effective design solution space and address much more design options. The DBMS is then the latest prototype platform which expands the scope of the AVDS system by addressing synthesis in further generic capability. It can custom build new synthesis systems and thus in a manner is a capability that can create Class IV synthesis systems according to the specifications of the project.

   Although DBMS addresses the design approach in a more generic manner than the AVDS and the Hypersonic Convergence, it is still in its developmental stages. As of now, it has been applied for sizing only the atmospheric hypersonic case-studies utilizing a scramjet propulsion system[74]. Currently, the DBMS capability presents a platform that has wide applicability but lacks maturation in terms of the disciplinary methods and data-base required for sizing SAV class vehicles. *This is recognized as one of the primary original contribution in terms of system development that is addressed through this research study by developing the required Data-Base and Knowledge-Base of disciplinary analysis methods library for the VTHL systems.*

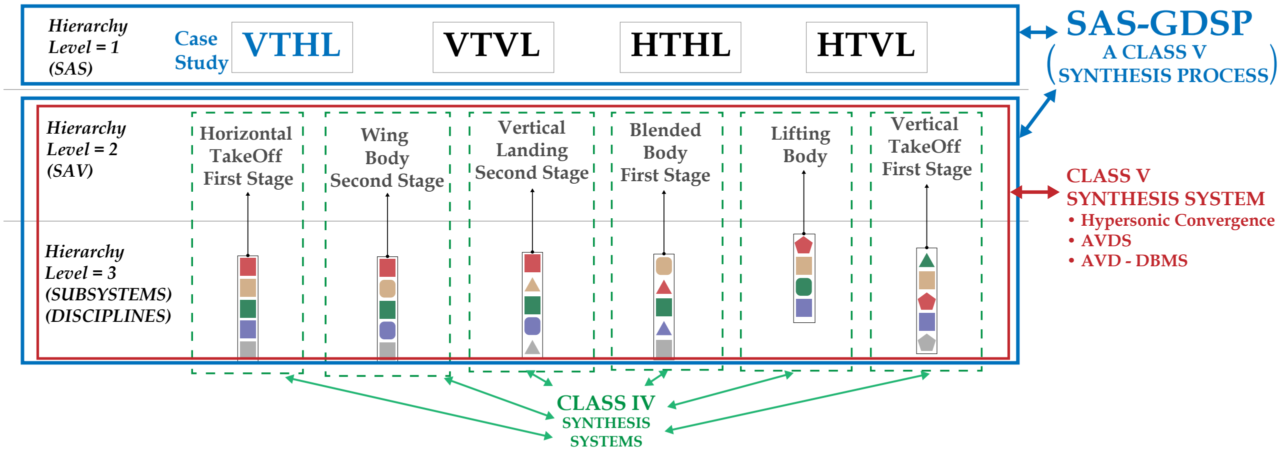


FIGURE 2.25 – SAS-GDSP increases the scope of CD assessment across vertical hierarchy levels, a unique capability missing from existing synthesis approach.

3. Despite the generic nature and wide applicability of these synthesis tools, it is found that their capability is only applicable for integrating subsystems disciplines to size and develop design solution spaces for a flight vehicle which exists at the hierarchy level-2 for the SAS, i.e. the SAVs. Although they can size both, the first stage and the second stage separately, these systems do not address the topmost hierarchy level of the SAS with the same consistent process and in the same cohesive manner as one system, as they do for the SAVs at the second hierarchy level.

   Hence, no Class V capability is found that is applicable at hierarchy level-2 and hierarchy level-1 consistently . The proposed SAS-GDSP in comparison presents a generic process that is applicable consistently to hierarchy level-2 as well as hierarchy level-1 because it is defined as a process and not necessarily a system (although a synthesis system is a crucial part of it, the SAS-GDSP expands beyond these synthesis systems). The SAS-GDSP thus proposes a best practice solution process that can be followed consistently for SAVs and SASs, independently. This notion is developed in Chapter 3 and validated for SAS hierarchy level-2 in Chapter 4 and for SAS hierarchy level-1 in Chapter 5 with results.

   In doing this, *SAS-GDSP does increase the scope of CD phase vertically* *across the SAS hierarchy. This aspect of the proposed solution is visualized in Figure 2.25 and is recognized as the fundamental original ideology contribution to the field of the multi-disciplinary sciences.*

4. Cost is mostly addressed in a very passive manner during the CD phase and is not actively used in making design decisions[25]. This is mainly because CD phase assessments are first order results and overlook many important factors that are important in assessing total life-cycle cost eg. manufacturing, operations et al. As a result, cost predictions in the CD phase are always unreliable and tend not to be a significant design driver.

   In contrast SAS-GDPS proposes to involve cost actively in the CD process. This is done by assessing cost estimates and normalizing it by the overall performance, then developing a solution space of this cost-performance matrix measure for the CD solution phase. In this manner, the accuracy of the cost phase is secondary as cost is now not used to predict overall cost estimates of the design but instead used as a comparative criteria in trade studies. The fundamental idea here is that even though cost estimates may be inaccurate to a certain degree, they are equally not true for all solution concepts considered. The primary intention is to not find the cheapest or the best performing vehicle but instead the one that gives best *performance-per-capita*. By including cost and mission analysis, the SAS-GDSP expands the scope of CD in horizontal direction and adds even more value to the results of CD that can help decision maker even further. *This recognized as the second fundamental original ideology contribution to the field of the conceptual design practices.*

### 2.4.2 System Specifications/Objectives:

The above discussion has shown the major features that the SAS-GDSP is required to address in order to effectively provide a comprehensive CD assessment capability for a generic SAS. The following traits have been identified as the basic tenets of a best-practice design tool and serve as the logical guidelines for this research.

» Physics based parametric modeling capability

» Systems level configurational assessment

» MDA based sizing implementation

» Fixed mission design convergence (with total system convergence proof)

» Solution space screening

---

[25] None of Hyp Cov, AVDS or DBMS has cost capability right now. Although DBMS platform provides capability to add cost as a disciplinary analysis method, it does not exist as such in its current state

» Cost-performance optimal design selection

The primary objective of this dissertation as stated initially is to advance the practices and capabilities of early design synthesis methodologies as applied to space access systems engineering, aimed at directly supporting the chief decision maker to add maximum value to the product. The specific objectives are defined which also act as the specifications for the SAS-GDSP:

1. Develop a generic design synthesis process applicable for all SAS configuration; SAS-GDPS.
2. Demonstrate applicability of the SAS-GDPS at the hierarchy level-2 for LRV segment of SAV level, proving SAS-GDPS as a generic Class IV synthesis methodology.
3. Develop a comprehensive data and knowledge library addressing primary disciplinary categories for LRV type SAVs.
4. Demonstrate applicability of the SAS-GDPS at the hierarchy level-1, proving SAS-GDPS as a generic synthesis process capable of synthesizing all generic SAS class.
5. Develop a disciplinary analysis methods library applicable for disciplines involved in the VTHL type SAS and verify the solution process along the selected design case-studies.

This chapter has provided a comprehensive review of the selected SAS case-study, the VTHL systems. Development of the AHP based analytical model for disciplinary assessment of the world-wide LRV programs is in itself a prototype approach to capture and quantify the knowledge contributions by legacy programs. Further, review of the design synthesis systems recognize the current capabilities for the CD phase and provides a significant understanding of where the current research study can contribute to advance the state of the art for the CD assessment capability. Following this the last section identifies the primary requirements for the SAS-GDSP and major specific objectives of the dissertation.

The next chapter will explain the solution process developed to satisfy these primary objectives.

Chapter 3

# LOGICAL SOLUTION ARCHITECTURE

*Logical Architecture describes how a solution works, in terms of function and logical information. It is used to show a static view of the solution implying connectivity between the elements and/or a dynamic view of the solution describing the process flow.*

» Warren Weinmeyer,
*An introduction to fundamental architecture concepts*
PowerPoint Slides

This chapter proposes the logical buildup to the solution. In the first section, the primary top-level system modules for the SAS-GDSP[1] solution are defined, providing a static view of the process. The second section then describes the overall development process for the primary system modules. The overall process is composed of four distinct System Development Processes (SDPs) leading to the creation of the SAS-GDSP. The third section describes the interconnection of the systems module and development processes providing the overall Logical Solution Architecture for the SAS-GDSP. The proposed solution is a four-step process that is generic in nature as every constituent module and development process is independent of the vehicle category or the system hierarchy level and is thus applicable to all four primary SAS categories.

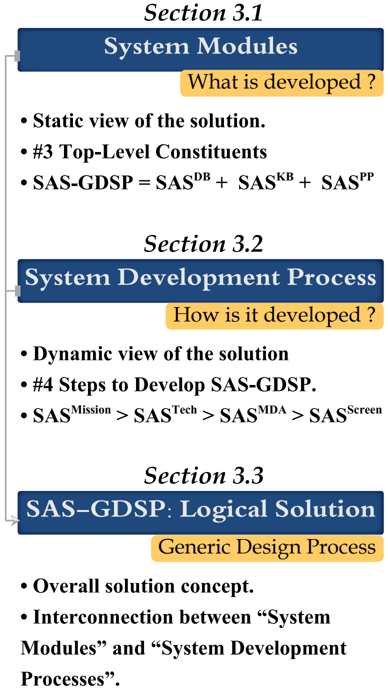


FIGURE 3.1 – Chapter-3 Overview

## 3.1 *Identifying Top-Level System Modules*

The review of the synthesis approaches in Chapter 2 provides a baseline understanding of the primary requirements for the SAS-GDSP. Following a top down approach here, the first step is to identify the primary modules that could be described as top level constituents of the proposed solution. Three primary system modules are defined next as; 1) Data-Base (DB) Module, 2) Knowledge-Base (KB) Module, and 3) Parametric-Processing (PP) Module. The first two modules, namely, DB and KB are developed by utilizing the organization structure in the JabRef Central Library (see, Section 2.1.2) while the third module, PP is developed through an application of the first two modules.

### 3.1.1 *Data-Base Module : $VTHL^{DB}$*

A significant common aspect of all of the design methodologies reviewed is that the conceptual design phase requires inputs and initial

[1] *SAS-GDSP*:Space Access Systems - Generic Design Synthesis Process

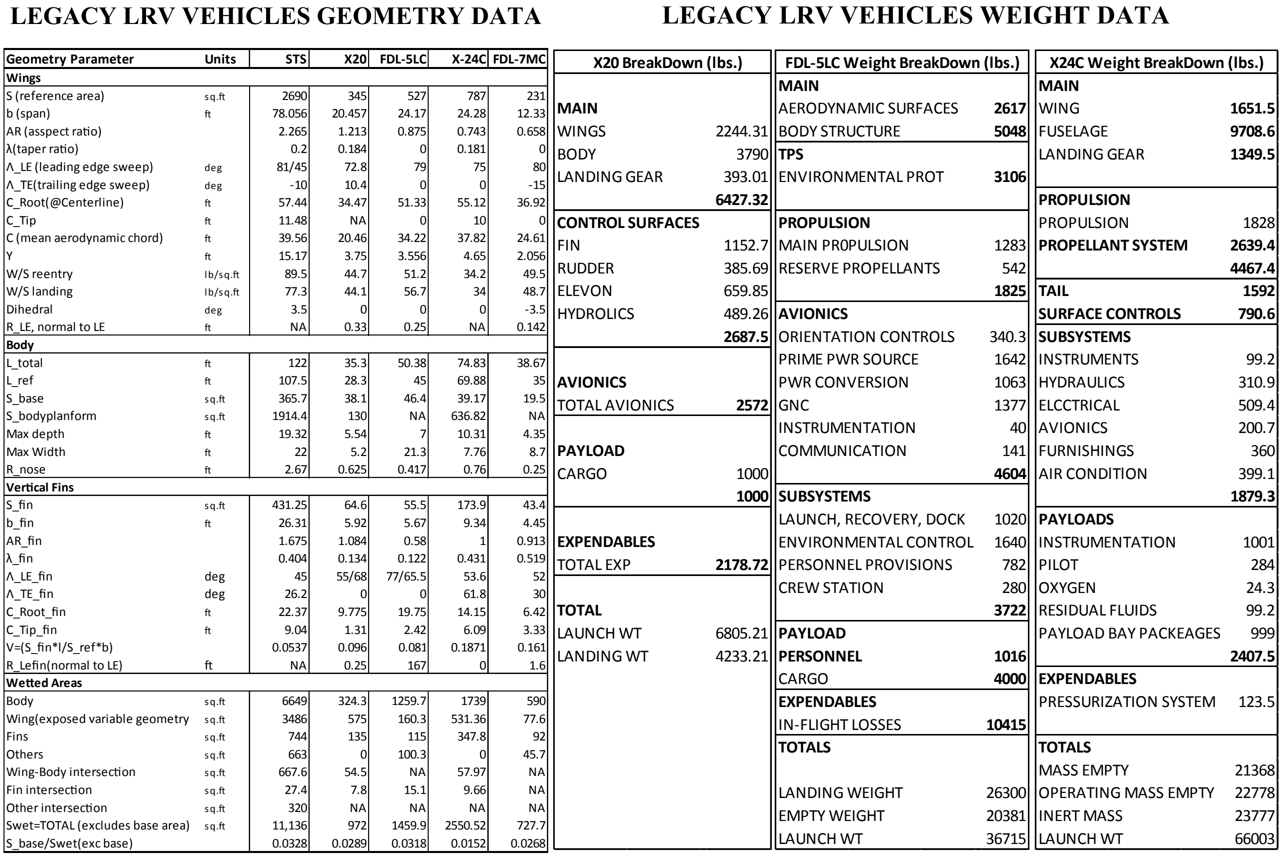
guess estimates based on past projects with similar missions requirements. The conceptual design phase is the first step where the vehicle is defined in terms of gross configuration selection, basic physical characteristics (gross mass, volume, size, etc.) and sub-system selection. The only input for this stage are the initial mission requirements which usually tend to be defined by the customer. Therefore, the majority of the initial inputs are best guess estimates based on trends and physical aspects of past projects of similar nature. To facilitate this demand, a VTHL-dedicated library is required to make best guess estimates at system and sub-systems level. This library is an organized collection of structured data pertaining to VTHL elements belonging to the first three hierarchy levels.

It must be noted here that the specific definition of 'Data' and 'Data-Sources' in Section 2.1.1 was done to this purpose. Data is defined as specific information applicable to one particular case, thus pertaining to specific vehicles (SAVs), design disciplines (aerodynamics, propulsion, structures etc.) or components (engines, control surfaces etc.) from past projects. The JabRef Central Library and the classification of literature sources was primarily implemented to organize and enable rapid access to the data-sources that represent main sources of VTHL data. Additionally, the survey of LRV programs done in Section 2.2.1 resulted in a structured data-base formulation for the LRV vehicles and related subsystems. Similarly, data-sources addressing specific existing and past LVs and related subsystems are also included in the $\text{VTHL}^{\text{DB}}$.

As an example, a source in the $\text{VTHL}^{\text{DB}}$ addresses one or more of following:

- Look-up tables of standard physics based data.
  (Eg. Standard atmospheric tables, propellant properties etc.)
- Physical Characteristics of Vehicles, sub-systems and components.
  (Eg. Overall physical properties of vehicles like the X-20[75] ($\text{TOGW}_{\text{X-20}}$, Planform $\text{Area}_{\text{X-20}}$), the Space Shuttle (STS) ($\text{Vol}_{\text{STS}}$, Wetted $\text{Area}_{\text{STS}}$) etc.)
- Performance estimates of vehicles and subsystems from the past programs. (Eg. Dyna-Soar aerodynamic performance[76], Description and Performance of the Saturn V Guidance Navigation & Control system (NASA TN D-5869)[77])
- Test-results from past vehicle projects and technology programs.

It should be noted that the DB is the collection of raw data for elements of a VTHL system and alone provides information about individual



**LEGACY LRV VEHICLES GEOMETRY DATA**

| Geometry Parameter | Units | STS | X20 | FDL-5LC | X-24C | FDL-7MC |
|---|---|---|---|---|---|---|
| **Wings** | | | | | | |
| S (reference area) | sq.ft | 2690 | 345 | 527 | 787 | 231 |
| b (span) | ft | 78.056 | 20.457 | 24.17 | 24.28 | 12.33 |
| AR (asspect ratio) | | 2.265 | 1.213 | 0.875 | 0.743 | 0.658 |
| λ(taper ratio) | | 0.2 | 0.184 | 0 | 0.181 | 0 |
| Λ_LE (leading edge sweep) | deg | 81/45 | 72.8 | 79 | 75 | 80 |
| Λ_TE(trailing edge sweep) | deg | -10 | 10.4 | 0 | 0 | -15 |
| C_Root(@Centerline) | ft | 57.44 | 34.47 | 51.33 | 55.12 | 36.92 |
| C_Tip | ft | 11.48 | NA | 0 | 10 | 0 |
| C (mean aerodynamic chord) | ft | 39.56 | 20.46 | 34.22 | 37.82 | 24.61 |
| Y | ft | 15.17 | 3.75 | 3.556 | 4.65 | 2.056 |
| W/S reentry | lb/sq.ft | 89.5 | 44.7 | 51.2 | 34.2 | 49.5 |
| W/S landing | lb/sq.ft | 77.3 | 44.1 | 56.7 | 34 | 48.7 |
| Dihedral | deg | 3.5 | 0 | 0 | 0 | -3.5 |
| R_LE, normal to LE | ft | NA | 0.33 | 0.25 | NA | 0.142 |
| **Body** | | | | | | |
| L_total | ft | 122 | 35.3 | 50.38 | 74.83 | 38.67 |
| L_ref | ft | 107.5 | 28.3 | 45 | 69.88 | 35 |
| S_base | sq.ft | 365.7 | 38.1 | 46.4 | 39.17 | 19.5 |
| S_bodyplanform | sq.ft | 1914.4 | 130 | NA | 636.82 | NA |
| Max depth | ft | 19.32 | 5.54 | 7 | 10.31 | 4.35 |
| Max Width | ft | 22 | 5.2 | 21.3 | 7.76 | 8.7 |
| R_nose | ft | 2.67 | 0.625 | 0.417 | 0.76 | 0.25 |
| **Vertical Fins** | | | | | | |
| S_fin | sq.ft | 431.25 | 64.6 | 55.5 | 173.9 | 43.4 |
| b_fin | ft | 26.31 | 5.92 | 5.67 | 9.34 | 4.45 |
| AR_fin | | 1.675 | 1.084 | 0.58 | 1 | 0.913 |
| λ_fin | | 0.404 | 0.134 | 0.122 | 0.431 | 0.519 |
| Λ_LE_fin | deg | 45 | 55/68 | 77/65.5 | 53.6 | 52 |
| Λ_TE_fin | deg | 26.2 | 0 | 0 | 61.8 | 30 |
| C_Root_fin | ft | 22.37 | 9.775 | 19.75 | 14.15 | 6.42 |
| C_Tip_fin | ft | 9.04 | 1.31 | 2.42 | 6.09 | 3.33 |
| V=(S_fin*l/S_ref*b) | | 0.0537 | 0.096 | 0.081 | 0.1871 | 0.161 |
| R_Lefin(normal to LE) | ft | NA | 0.25 | 167 | 0 | 1.6 |
| **Wetted Areas** | | | | | | |
| Body | sq.ft | 6649 | 324.3 | 1259.7 | 1739 | 590 |
| Wing(exposed variable geometry | sq.ft | 3486 | 575 | 160.3 | 531.36 | 77.6 |
| Fins | sq.ft | 744 | 135 | 115 | 347.8 | 92 |
| Others | sq.ft | 663 | 0 | 100.3 | 0 | 45.7 |
| Wing-Body intersection | sq.ft | 667.6 | 54.5 | NA | 57.97 | NA |
| Fin intersection | sq.ft | 27.4 | 7.8 | 15.1 | 9.66 | NA |
| Other intersection | sq.ft | 320 | NA | NA | NA | NA |
| Swet=TOTAL (excludes base area) | sq.ft | 11,136 | 972 | 1459.9 | 2550.52 | 727.7 |
| S_base/Swet(exc base) | | 0.0328 | 0.0289 | 0.0318 | 0.0152 | 0.0268 |

**LEGACY LRV VEHICLES WEIGHT DATA**

| X20 BreakDown (lbs.) | |
|---|---|
| **MAIN** | |
| WINGS | 2244.31 |
| BODY | 3790 |
| LANDING GEAR | 393.01 |
| | **6427.32** |
| **CONTROL SURFACES** | |
| FIN | 1152.7 |
| RUDDER | 385.69 |
| ELEVON | 659.85 |
| HYDROLICS | 489.26 |
| | **2687.5** |
| **AVIONICS** | |
| TOTAL AVIONICS | **2572** |
| **PAYLOAD** | |
| CARGO | 1000 |
| | **1000** |
| **EXPENDABLES** | |
| TOTAL EXP | **2178.72** |
| **TOTAL** | |
| LAUNCH WT | 6805.21 |
| LANDING WT | 4233.21 |

| FDL-5LC Weight BreakDown (lbs.) | |
|---|---|
| **MAIN** | |
| AERODYNAMIC SURFACES | **2617** |
| BODY STRUCTURE | **5048** |
| **TPS** | |
| ENVIRONMENTAL PROT | **3106** |
| **PROPULSION** | |
| MAIN PR0PULSION | 1283 |
| RESERVE PROPELLANTS | 542 |
| | **1825** |
| **AVIONICS** | |
| ORIENTATION CONTROLS | 340.3 |
| PRIME PWR SOURCE | 1642 |
| PWR CONVERSION | 1063 |
| GNC | 1377 |
| INSTRUMENTATION | 40 |
| COMMUNICATION | 141 |
| | **4604** |
| **SUBSYSTEMS** | |
| LAUNCH, RECOVERY, DOCK | 1020 |
| ENVIRONMENTAL CONTROL | 1640 |
| PERSONNEL PROVISIONS | 782 |
| CREW STATION | 280 |
| | **3722** |
| **PAYLOAD** | |
| **PERSONNEL** | **1016** |
| CARGO | **4000** |
| **EXPENDABLES** | |
| IN-FLIGHT LOSSES | **10415** |
| **TOTALS** | |
| LANDING WEIGHT | 26300 |
| EMPTY WEIGHT | 20381 |
| LAUNCH WT | 36715 |

| X24C Weight BreakDown (lbs.) | |
|---|---|
| **MAIN** | |
| WING | **1651.5** |
| FUSELAGE | **9708.6** |
| LANDING GEAR | **1349.5** |
| **PROPULSION** | |
| PROPULSION | 1828 |
| **PROPELLANT SYSTEM** | **2639.4** |
| | **4467.4** |
| **TAIL** | **1592** |
| **SURFACE CONTROLS** | **790.6** |
| **SUBSYSTEMS** | |
| INSTRUMENTS | 99.2 |
| HYDRAULICS | 310.9 |
| ELCCTRICAL | 509.4 |
| AVIONICS | 200.7 |
| FURNISHINGS | 360 |
| AIR CONDITION | 399.1 |
| | **1879.3** |
| **PAYLOADS** | |
| INSTRUMENTATION | 1001 |
| PILOT | 284 |
| OXYGEN | 24.3 |
| RESIDUAL FLUIDS | 99.2 |
| PAYLOAD BAY PACKEAGES | 999 |
| | **2407.5** |
| **EXPENDABLES** | |
| PRESSURIZATION SYSTEM | 123.5 |
| **TOTALS** | |
| MASS EMPTY | 21368 |
| OPERATING MASS EMPTY | 22778 |
| INERT MASS | 23777 |
| LAUNCH WT | 66003 |

TABLE 3.1 – Physical Characteristics Data Sets of legacy LRV vehicles created through $\text{VTHL}^{\text{DB}}$

cases[2]. Table 3.1 shows example of geometric and weight data characteristics of the some legacy LRV vehicles created as a part of $\text{VTHL}^{\text{DB}}$. Further similar data tables were created for the LRV design disciplines and LVs and are given in the following chapters where required.

### 3.1.2 *Knowledge-Base Module : $\text{VTHL}^{\text{KB}}$*

Knowledge is an abstract term which can be used in many references based on the implication and application of the concept. Everything known can be called as knowledge in a very broad sense. In context of this application, knowledge is defined in Section 2.1.1 as the generic information that addresses more than one particular case. Hence the literature source addressing information applicable to a class of systems or sub-systems is a knowledge source as it is applicable to all the cases under that particular classification. These literature sources are identified exclusively in the JabRef Central Library, thereby enabling to define and organize the $\text{VTHL}^{\text{KB}}$ library within the JabRef system[3] by assigning specific keywords that help to scan and identify required

[2] A total of 403 references form the $\text{VTHL}_{\text{DB}}$.

[3] A total of 246 reference sources form the $\text{VTHL}^{\text{KB}}$.

information.[4]

As mentioned earlier, the CD phase assessment is primarily addressed by a multi-disciplinary framework where first-order disciplinary analysis is integrated to establish concept feasibility. Hence, an example for a primary type of knowledge then would be the classical analytical equations found in most textbooks which are used as disciplinary analysis methods as they are correlating several variables in an input-output type manner. When the inputs deck is specified for a particular case, the output is solved for only that specific set of inputs. A basic example of this case is the well known rocket equation which correlates vehicles mass-ratio and fuel energy (via variable Isp) to calculate vehicle's performance measure. It is a generic information which can be applied to any specific selection of vehicle, fuel and rocket engine, thus giving performance measure for that specific selection of elements. Similarly, a generic aircraft design methodology like Loftin or PrADO is an example of a multi-disciplinary knowledge source. Coleman[27] identifies the significance of a 'process and methods library' which is defined here as the Knowledge-Base as follows: *"A well organized and condensed Process Library and Disciplinary Methods Library would provide the designer with a quick reference to the tools available, how and when to use them. Such a library would provide the elements for a rapid adaptation of a design process to a new design problem to be solved."*

A source in VTHL$^{KB}$ module addresses these types of information:

- Standard classical textbook-based disciplinary analysis methods.
  (Eg. Rocket equation, trajectory analysis methods etc.)
- Existing empirical methods based on the data-correlation for a class of vehicles or subsystems. These methods are usually created by identifying characteristic generic trends observed by conducting tests or analysis for a for several elements of a same group.
  (Eg. Aerodynamic Characteristics of Reentry Configurations[78].)
- Design synthesis MDAs and integration processes addressing a class of vehicles (i.e. a configuration)[5] (Eg. Loftin, Hunt, Hypersonic Convergence AVDS etc.)
- Heuristics and general trends that indicate some charateristic features of a class and help make design decisions. These are different from empirical methods since these are not quantified but are qualitative description of non-tangible or salient aspects of vehicles.

The application of the KB module in developing empirical data-base disciplinary methods and recognizing characteristic trends is shown in Figure 3.2. The first plot is from a NASA technical report[79] where

[4] Standard Keywords like 'Methods' and 'Analysis' with each discipline ('Aerodynamics', 'Propulsion' etc) help to find and select the required methods.

[5] A Generic Class V MDA represents a higher knowledge capability than a Class IV which is only applicable for one particular configuration. A Class IV MDA is also a knowledge source as it can be applied to size several individual cases all belonging to same configuration. An MDA developed for only one specific vehicle/project like SSSP is then a type of DB source as it is applicable only for one particular case.

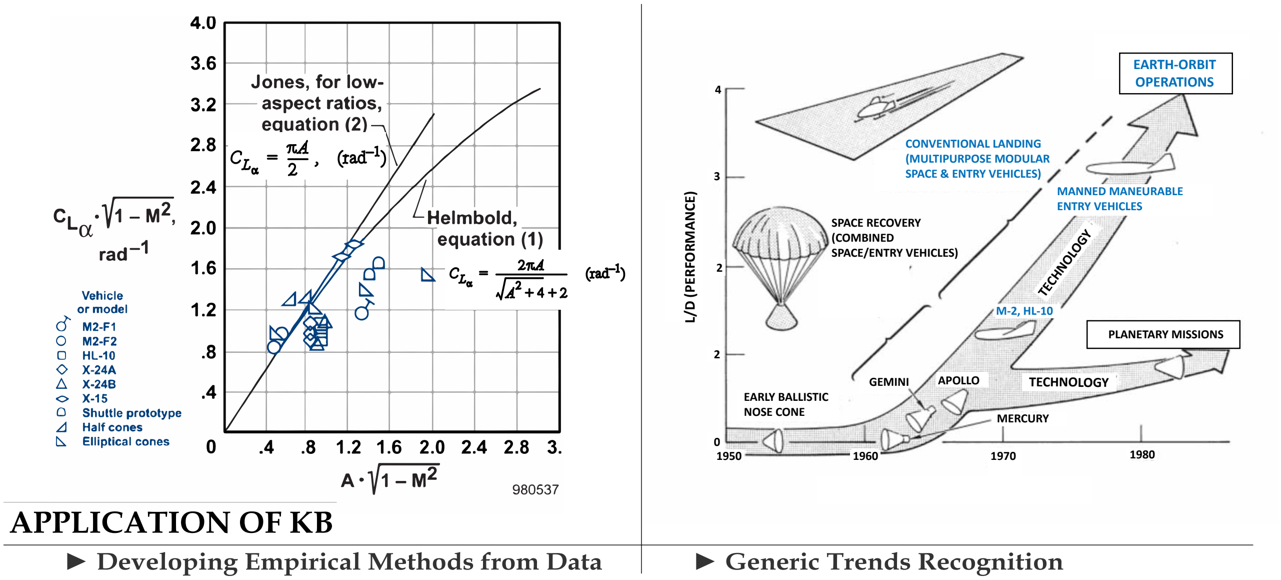


FIGURE 3.2 – Individual vehicle's data and characteristics when assessed for a generic class can be used to develop new methods and useful insights for future application. The first plot is reproduced from Saltzman et al.[79] and the second part of the Figure is reproduced from Loh [80]

the flight determined aerodynamic performance test data for several legacy program was used by Saltzman, Wang and Iliff to "provide a useful analytical framework with which to compare and evaluate new vehicle configurations of the same generic family." The second part of the Figure shows generic characteristic trends for reentry vehicles is taken from Loh[80].

### 3.1.3 *Parametric Processing Module : VTHL$^{PP}$*

While 'Data' is the information related to one specific entity, 'Knowledge' is continuum information that relates several specific entities showing similar nature. This is the fundamental logic of defining a class or a group and the definition of data and knowledge provided here are backtracked from this logic. In the context of the MDA framework, disciplinary methods analysis and empirical estimates are used together to solve for individual subsystems under mission specific constraints where all these factors are governed by the primary objectives for the mission. For example, a subsonic aircraft would confine to a different set of constraints than a hypersonic test demonstrator and hence the analysis methods used for a hypersonic propulsion system analysis would also be based on a different set of physics. The methods and data for both mission classes cannot be interchanged, but can be applied to different cases from the same class[6]. Also these methodologies and constraints are integrated together by a synthesis logic that forms the multi-disciplinary framework. This combination of data and knowledge in a specific manner is recognized as the development step

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[6] A performance analysis method for subsonic aerodynamics can be used for a Boeing-747 and Airbus A-380 but not applicable for the Bell X-1

for the Parametric Processing module.

Since parametric sizing is the most essential path-finding design step during the CD phase assessment and is applied in the MDA framework. The term sizing refers to the process of calculating the fundamental physical characteristics of the vehicle, namely, size or the geometry measures and the weights calculation. It is the first step where mission requirements along with gross configuration concepts and disciplinary assumptions are used for a first-order evaluation in a multi-disciplinary analysis to identify the gross physical characteristics at the system and sub-system level.[7] In Coleman's words, *"Generally speaking, sizing is an underdetermined system (more unknowns than equations). Therefore, we must assume certain unknowns constant and then solve the remaining. The solution for the specific sizing problem posed is called the sizing logic."*[27]

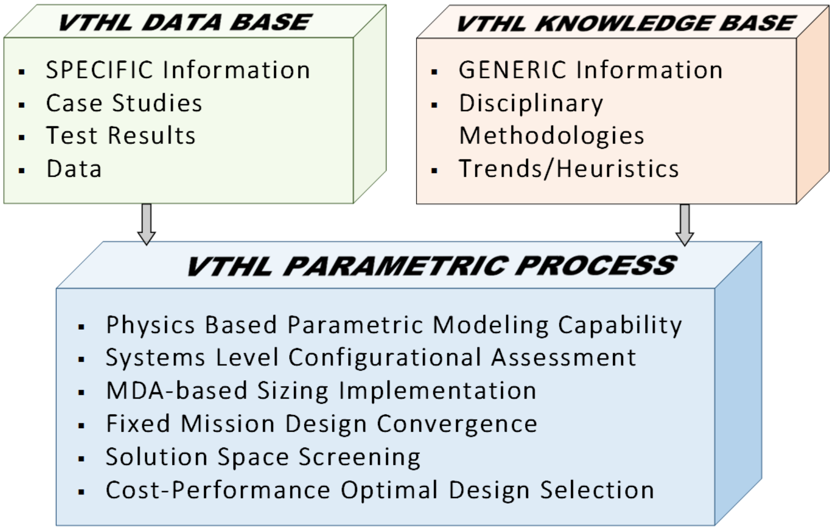

FIGURE 3.3 – The top-level systems module show the static view of the SAS-GDSP solution with interconnections between three primary solution components.

The above discussed three modules are the primary top-level components required to develop the SAS-GDSP. The interrelationship among these modules is shown in Figure 3.3, where it can be seen that the DB and KB modules feed into the PP module. The initial assumptions stemming from the *DataBase* Library are made up of previous VTHL projects. At the same time, the synthesis kernel[8] is composed of several disciplinary analyses modules working coherently towards sizing a converged total system. These disciplinary methods and configurational trends are residing in the Knowledge-Base Library. The two libraries feed information to the VTHL Sizing tool which in itself is the multi-disciplinary module processing that information (combination of Data and Knowledge) to converge design solution and generate feasible solution-space.

[7] Sizing application for the hypersonic vehicles: "The design problem posed with hypersonic aircraft requires an advanced sizing logic since the hypersonic flight vehicle is a fully blended geometry, where the blended body must perform all functions (volume generation, lift generation, integrated propulsion, stability and control)".
- Garry Coleman

[8] See Section 4.3.3

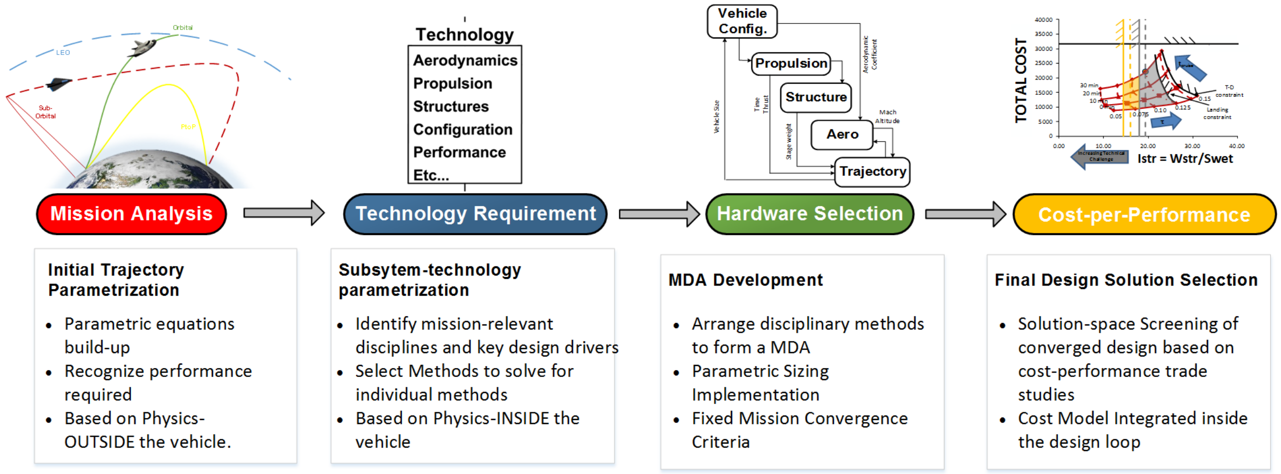

FIGURE 3.4 – System Development Processes as building blocks of Logical Solution

Although the most significant application of the PP module is found in the creation of the MDA framework with the implementation of the sizing step, this module by definition can be utilized in domains outside the MDA framework as well, as further explained in the next section.

## 3.2 *System Development Process*

The three System Modules define the top-level components of the SAS-GDSP and provide a static view of the logical solution architecture showing the connectivity between the primary modules. This section now provides a dynamic view of the logical solution architecture in four distinct system development processes leading to the development of the primary three modules. The four distinct processes (SDP) are representative of *what needs to be done to develop the generic SAS synthesis capability*, based on the specifications defined in Section 2.4.

The four development processes are shown in a sequential order of execution in Figure 3.4. Each phase leads on to the next in terms of concepts and processes development. Next is the overview description of each step.

### 3.2.1 *Mission Analysis*

Mission objectives are the first set of inputs that represent the primary performance requirements the vehicle must be able to achieve (usually in terms of range, altitude, payload capacity etc). This notion is the fundamental idea to begin the system development process for the SAS-GDSP. The ECSS[9] Secretariat of ESA-ESTEC produced a series of 'Standards' for management, engineering and product assur-

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[9] European Cooperation for Space Standardization

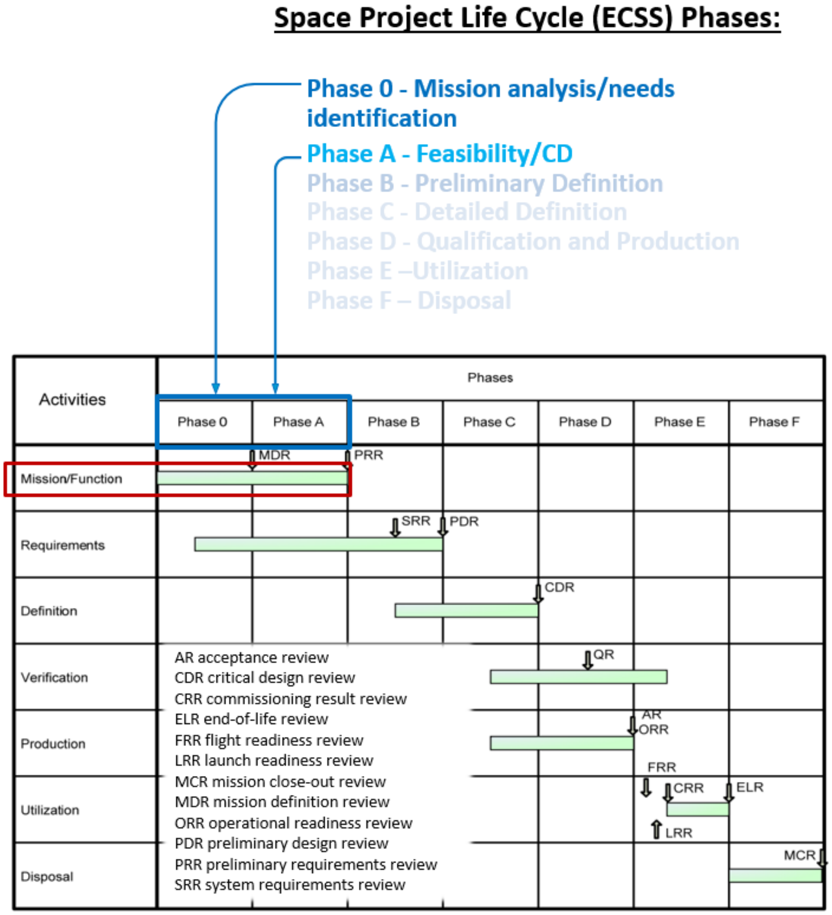
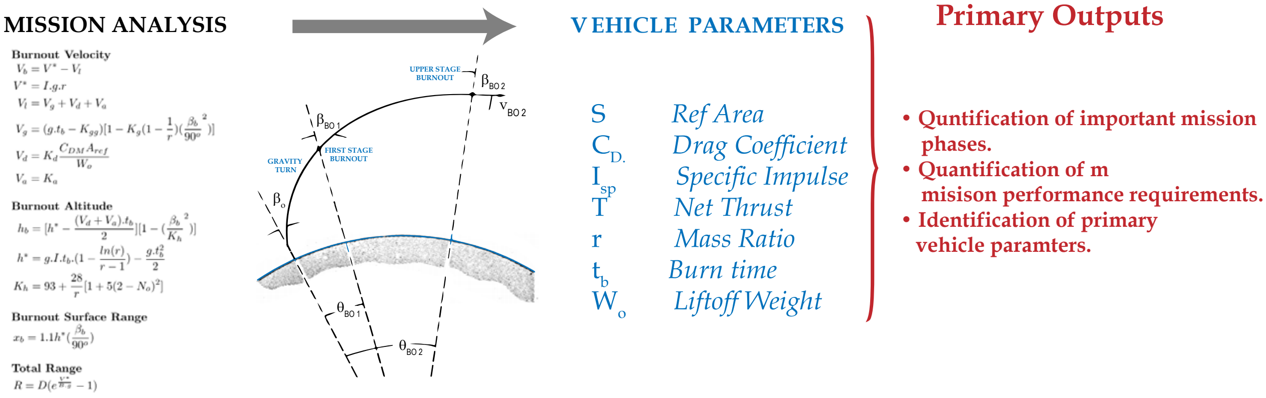


FIGURE 3.5 – Mission Analysis is identified as the precursor step to the CD phase by the ESA-ESTEC. Reproduced here from the ECSS Standard[81].

ance in space projects and applications, where the Project planning and implementation[81] standard address the project phasing and the typical life cycle of a space project. This is shown in Figure 3.5 where the Mission Analysis is shown as a Phase 0 step identifying the primary needs of the project and a precursor to the Phase A, the CD/Feasibility phase. Wertz & Larson identify the same notion in the well-known *Space Mission and Analysis* text[82] for ESA, NASA and DoD (see Table 1-2, in Section 1.2 of the text).

The SAS conceptual design should begin by developing initial mission concepts represented by the mission flight path parametrization, based on these primary performance requirements. This aspect is addressed in the first SDP, the Mission Analysis.

Mission Analysis is defined as the first SDP where the primary focus is to generate a parametric model of physics-based equations composed of the most important flight path variables of each mission phase. This section provides a parametric representation of the indi-



**MISSION ANALYSIS**

**Burnout Velocity**

$V_b = V^* - V_l$

$V^* = I.g.r$

$V_l = V_g + V_d + V_a$

$V_g = (g.t_b - K_{gg})[1 - K_g(1 - \frac{1}{r})(\frac{\beta_b}{90^o}^2)]$

$V_d = K_d \frac{C_{DM} A_{ref}}{W_o}$

$V_a = K_a$

**Burnout Altitude**

$h_b = [h^* - \frac{(V_d + V_a).t_b}{2}][1 - (\frac{\beta_b}{K_h}^2)]$

$h^* = g.I.t_b.(1 - \frac{ln(r)}{r-1}) - \frac{g.t_b^2}{2}$

$K_h = 93 + \frac{28}{r}[1 + 5(2 - N_o)^2]$

**Burnout Surface Range**

$x_b = 1.1h^*(\frac{\beta_b}{90^o})$

**Total Range**

$R = D(e^{\frac{V^*}{R.g}} - 1)$

**VEHICLE PARAMETERS**

| | |
|---|---|
| $S$ | *Ref Area* |
| $C_{D.}$ | *Drag Coefficient* |
| $I_{sp}$ | *Specific Impulse* |
| $T$ | *Net Thrust* |
| $r$ | *Mass Ratio* |
| $t_b$ | *Burn time* |
| $W_o$ | *Liftoff Weight* |

**Primary Outputs**

- **Quntification of important mission phases.**
- **Quantification of m misison performance requirements.**
- **Identification of primary vehicle paramters.**

FIGURE 3.6 – The parametric Mission Analysis distinctly recognize the primary design driving variables that affect the most important mission performance requirements.

vidual mission segments i.e. launch, staging, orbit, reentry, descent, land etc., in terms of significant physical parameters. For example, the launch phase would be quantified in terms of delta V required to achieve a specific altitude orbit. Similarly, the reentry phase is typically dominated by the heating effects and therefore, variables like heat transfer rate and maximum temperature etc. become of primary importance. The primary purpose of mission analysis is to identify the most important physical effects that the influence and drive the design solution.

Dergarabedian & Dyke in a 1963 report [83] provide a significant design insight with the following words;

> *"The vehicle parameters can be divided into two categories:* vehicle design parameters and trajectory parameters... *We usually think of mission in terms of trajectory parameters and vehicles in terms of design parameters and the problem becomes to relate the two."*

The main take-away from this insight is the distinct identification of the primary design variable and the primary performance requirements. Figure 3.6 shows the classical rocket equation as the primary mission analysis equation for the boost or ascent phase of the launch vehicle. Mission analysis provides the primary mission variables (as shown on the right hand side of the Figure) required to characterize the performance requirements of a launch vehicle. These performance variable (referred to as the trajectory variable by Dergarabedian & Dyke) are a function of the parameters that characterize the vehicle and its subsystems (which are shown on the left side of the Figure). In other terms, the mission or trajectory variables identify the *physics taking place outside the vehicle*. These variables are non-tangible parameters that measure and quantifies how the tangible system performs in the real-time physical realm.

The key parameters of this phase are indicative of the performance

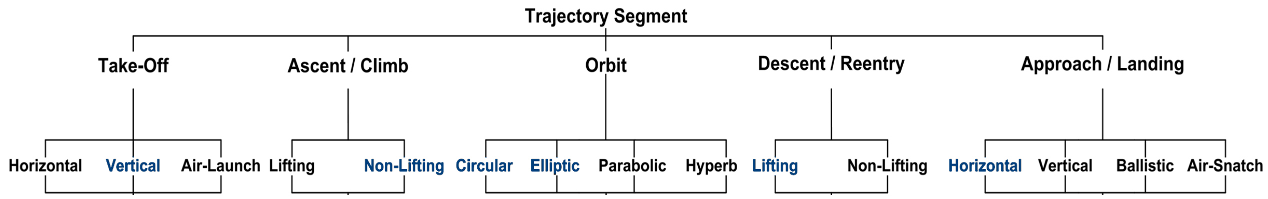


FIGURE 3.7 – Various trajectory options exist for a SAS mission. The highlighted options are applicable for the VTHL case-study.

requirements of the vehicle. The equations are usually calculating a performance parameter as function of vehicle parameter. It must be noticed that every mission section could be executed in several ways and therefore different combinations make a new mission, see Figure 3.7. The focus here is to generically identify these phases using physics based parametric equations which calculate flight path variables as a function of vehicle based parameters.

### 3.2.2 *Technology Requirement*

The second SDP step is called the Technology Requirement. The fundamental notion of this step is the quantification of the subsystems' technology requirements that can meet the mission performance needs.[10] To that effect, this SDP takes the physical parametric model generated in the Mission Analysis, back-tracks the vehicle parameters that represents primary design disciplines for respective subsystems and it does recognize the primary output required for each disciplinary analysis. Since these parameters influence the design of the vehicle directly, they represent *the physics inside the vehicle that can be changed to provide output as required by the mission parameters*. Note that the information shown in Figure 3.6 shows both the mission and the vehicle parameters.

Clearly, the vehicle design parameters for a vertical launch vehicle describe the physical rocket and include such quantities as weights, thrusts, propellant flow rates, drag coefficients, and the like. Dergarabedian & Dyke further comment on the vehicle parameters as follows; *" A set of these parameters would serve as a basic set of specifications with which to design a vehicle. Trajectory parameters include such quantities as impact range, apogee altitude, and burnout velocity. A particular vehicle system can perform many missions and any one mission can be performed by many vehicles. We usually think of mission in terms of trajectory parameters and vehicles in terms of design parameters and the problem becomes to relate the two."* Carrying on the example of velocity requirement, delta V of the launch is dependent on mass ratio which is again dependent on individual mass components. In contrast, reentry heat analysis depends on L/D, surface area, geometry etc.

The primary outcome of this step is the identification of subsystem

[10] The subsystems here imply the constituent elements. For a SAV, they are the involved disciples while for a SAS, they are the constituent SAV that integrate together to form the SAS.

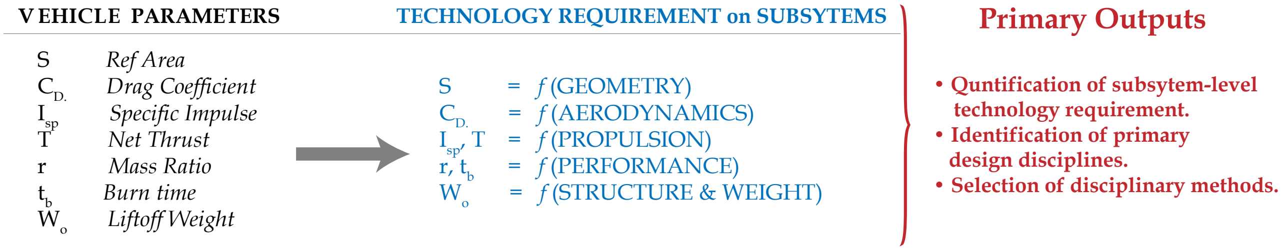


FIGURE 3.8 – Primary vehicle parameters identified in Mission Analysis are used to identify disciplinary methods and quantify subsystems technology requirements.

disciplines and respective disciplinary variables. These variables then provide guidelines with which the designer could now select disciplinary analysis methods that compute those variables. As a result, this section identifies the technology required at subsystems level to meet the mission objectives.

### 3.2.3 *Hardware Selection*

The next SDP is termed as the Hardware Selection. Primary notion of this step is to use the information developed in the Technology Requirement SDP representing the subsystems and integrate them together in a feasible working hardware unit. To implement the integration and feasibility, this step takes input from the previous step in terms of the technology requirements for the subsystems and creates an MDA that arranges and manipulates the disciplinary arrangement (in form of information flow from one discipline to next) to match the mission performance requirements identified in Mission Analysis.

The output generated here is a multi-disciplinary module that parametrizes the individual disciplines and combines them together to provide first, a selection and then, combination of subsystems. This is the execution phase where the parametric sizing is executed such towards converging the solution to give the first estimates of vehicle hardware's physical characteristics. The *Mission Analysis* and the *Technology Requirements* steps also provide constraints to assess feasibility of the concept.

At this stage the MDA creation and execution is implemented with the main objective of creating a solution space topography of converged design concepts. This is the critical outcome of the MDA framework which is achieved by trading configuration, technology and mission parameters. The key idea is to identify and develop several design concepts options that match the performance requirements of the mission, thus providing a range of solutions rather than a fixed design point.

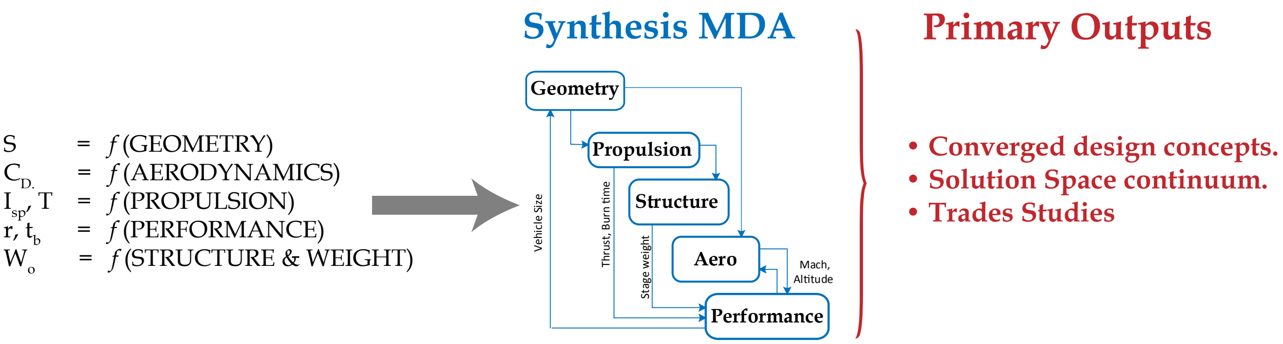


FIGURE 3.9 – Disciplinary integration into MDA synthesis to generate feasible vehicle hardware concepts and create solution space continuum of converged vehicles.

### 3.2.4 *Cost-per-Performance Trade Space Screening*

The hardware selection SDP ends with the creation of multiple design concepts presented in a solution space topography. This serves as an input to the last SDP step of the process that performs cost analysis for the solution space consisting of a range of individual design points. The important aspect to note here is that in the traditional sense, cost is usually performed outside the design loop. The usual practice is to select a final design point from the solution space based on performance/technology criteria and then perform cost analysis for that final design point, thus providing an initial cost estimate. As it is seen time and time again, the cost estimate at the conceptual design phase is never accurate and thus holds low value in decision making processes as a number of new factors are encountered in the preliminary and detailed design phases. Consequently, this research follows a different approach since cost analysis is integrated into the sizing process where cost is calculated for every feasible design point in the solution space generated as the output of the previous SDP. In this manner, accuracy of the cost figures is not the key but the relative comparative trends differentiating design alternatives.

The primary purpose for including cost estimation during the CD phase is to enable a consistent cost comparison among all the potential vehicle solutions for those sized to perform the mission. The final cost estimate for every design point is normalized by a non-dimensional overall performance measure index. This marks the last step in the baseline vehicle selection and it executes a cost-per-performance analysis to select the vehicle that provides the best cost-per-performance results. That is the vehicle that performs best per cost unit. Total accuracy of the cost analysis in this application is of secondary importance since the analysis is *NOT* done on one optimal vehicle alone but for the vehicle continuum throughout the feasible solution space, thus making a consistent-comparison among the valid design points throughout the solution space continuum. Note that the intention is not to predict the final cost (as cost estimates at the CD phase tend to be usually inaccurate), but to identify the most performance/cost optimal vehicle. Therefore, this final step chooses not the highest performing vehicle or the cheapest but rather the one that adds maximum value for the price while still delivering essential mission requirements.

## 3.3 *Complete Logical Solution Architecture*

The top-level System Modules (DB, KB, PP) are the primary component element which represent the static view of the solution while the SDPs (Mission-Technology-Hardware-Cost) are the execution steps which represent the dynamic view of the solution. The significant aspect here is the generic nature as every constituent module and development process is independent of the vehicle category or the system hierarchy level and is thus applicable for all four primary SAS categories. The complete logical solution architecture for the SAS-GDSP then is the combination of both these aspects.

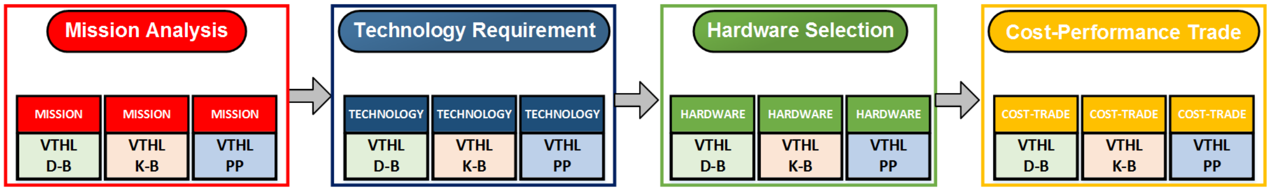


FIGURE 3.10 – Every SDP is made of elements from the Data, Knowledge and Parametric processing module. In this representation of the Logical Solution Architecture, the sequential order of four SDPs is necessary.

The four SDPs assemble into a sequential process where each step provides the input for the next. Since every SDP is generic in nature and acts as a partial segment of the overall solution process addressing the CD phase assessment, each of the four SDP is representative of a process at the end of which certain deliverables are produced which in turn serve as input to the next phase. Every phase is buildup using elements from the data, knowledge and parametric modules that finally comprise to the top level systems elements and tie up the processes to the top-level modules. This then completes the logical solution architecture discussion. Figure 3.10 first shows how all four SDPs are composed of elements from the three system modules. This shows the overall decomposability[11] of the process. Next, it is shown that individual modules are then the sum of components from the four SDPs, see Figure 4.1. It must be noted here that the SDPs are sequential in nature, but that the sum of their portions in the system modules is not sequential. This means that the order of the four SDP in Figure 3.10 is necessary, but is not required or needed in the data, knowledge or

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[11] *Decomposability in Software Testing:*
1. By controlling the scope of testing, problems can be isolated quickly, and smarter testing can be performed.
2. The software system is built from independent modules.
3. Software modules can be tested independently in Software Testing

parametric elements in Figure 4.1.

When combined together, it can be seen that these steps demonstrate a generic design synthesis process for the conceptual design phase that is independent of the configuration or the hierarchy level. This concept will be implemented and demonstrated in Chapters 4 and 5 next.

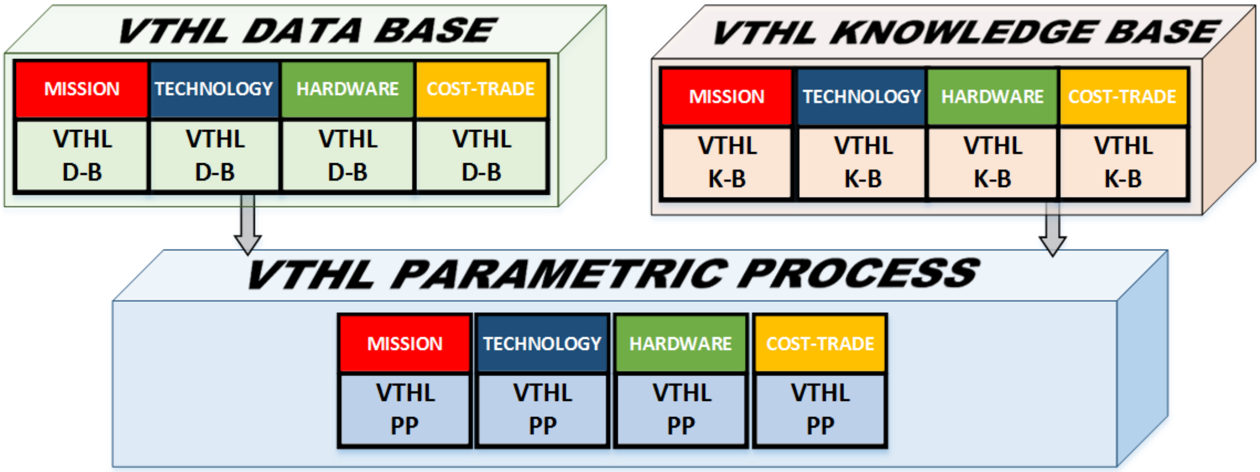

FIGURE 3.11 – The three modules are sum of data, knowledge and process elements executed in every SDP step. This implies the decomposable nature of the solution process.

*Chapter 4*

# PHYSICAL SOLUTION ARCHITECTURE IMPLEMENTATION OF THE SAS-GDSP FOR SAV AT HIERARCHY LEVEL 2

> *Physical Architecture refers to specific products, protocols, and data representation where/when/if it is architecturally salient to do so. It is the least abstract representation and typically is very detailed.*

» Warren Weinmeyer,
An introduction to fundamental architecture concepts
PowerPoint Slides

The logical solution architecture of the SAS-GDSP as explained in the last chapter is applied here for the hierarchy level-2 (the SAV) of the the SAS. Only the LRV segment of the SAV is sized here to demonstrate the application of the SAS-GDSP at hierarchy level-2.

The first section provides the general description of the LRVs, the generic classes of the LRVs, the overall disciplinary trade matrix and defines the LRV case-studies selected for the sizing study. This section identifies the significant advantages of using the AVD Laboratory inhouse synthesis capability, the DBMS platform, as a part of the overall SAS-GDSP.

The next section then provides an overview of the DBMS system to give the reader a clear idea of how and in what segments of the SAS-GDSP the DBMS is applied.

The third section provides the description of the physical solution architecture for the LRV application. This entails a detailed description of the four system development processes of the SAS-GDSP which have been first introduced in the previous chapter.

The fourth section then provides the discussion of the results from the application of the SAS-GDSP solution to the LRV case-studies.

## 4.1 SAV Case Study: LRV

The Lifting Reentry Vehicles (LRV) have been surveyed exhaustively in the literature review, see Section 2.2.1, Chapter 2. The review covered 60 projects from the 1933 Sänger Silbervogel to the current under-development vehicles across the globe. The first part of the review covered a disciplinary assessment of the vehicles, while a subsequent review surveyed the projects for the comprehensive documentation of the CD phase assessment. The overall review covers extensive literature published for the LRV class of vehicles, and it is built upon the information provided by representative 172 literature sources. Throughout this extensive survey, an in-depth understanding of the physical and operational characteristics of LRV vehicles in general has been gained. This understanding is utilized in the following section to execute the SAS-SGDP solution process as applied to the LRV class of the SAVs.[1]

### *4.1.1 LRV Classes*

Based on the geometric configuration variety, the LRV can be classified in three following primary classes.

1. Wing-Body (WB): An aircraft like geometry configuration where the fuselage provides the main housing volume storing most of the payload and components, while the highly swept wing acts as the primary lift producing hardware component. Most of the early LRV designs were wing-body configurations (eg. Sänger's Silbervogel, Dorberger & Ehricke's Bell studies, Bell BOMI, BRASS, X-20 etc). Currently, the USAF X-37-B is the only operational LRV, also a wing body configuration.
2. Lifting-Body (LB): Lifting-body configurations are primarily all-body vehicles which produce lift using the body, thus they do not require wings. Some of the first attempts to use a lifting body dates back to the early NASA lifting body programs in the 1960s. Since then, numerous programs and studies have looked into employing LB configurations for LEO and other missions. Two distinct types of LB configurations have been explored primarily based on the nature of underside geometry of the body, namely, round bottom LBs (eg. HL-10, M2-F2, Bor-4, HL-20, X-23, X-24A during the early days of the NASA LB programs) and the flat-bottom LBs (eg. X-24B, FDL-5, FDL-7, Model 176). Flat bottom LBs demonstrate a higher range performance capability compared to round bottom LBs.[2]
3. Blended-Body(BB): This LRV configuration is a blend of WB and LB geometries, and it is defined as a vehicle having no clear dividing line between the wings and the main body of the craft. A typical feature present with the BB is the more substantial joining or blending feature between the wing and body compared to just a typical fairing. The Boeing X-48 or X-45 are some of the most popular BB configuration examples in the aircraft realm, while the application of BB in the orbital LRV missions has been limited to a very few concepts so far like the Lockheed D-21 and X-24C/L-301.

These three categories comprehensively cover the LRV class of SAVs. Next is the description of the case-studies selection that will be used

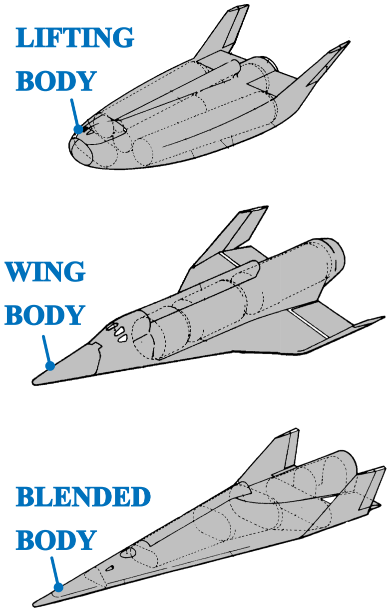

FIGURE 4.1 – Three primary types of the LRV configurations.

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[1] The other segment of the SAV hierarchy class is the LVs which are not parametrically sized like the LRV case here but rather selected as a combination of multiple constituent stages.

[2] see Appendix B, Section A.1.2 for further details

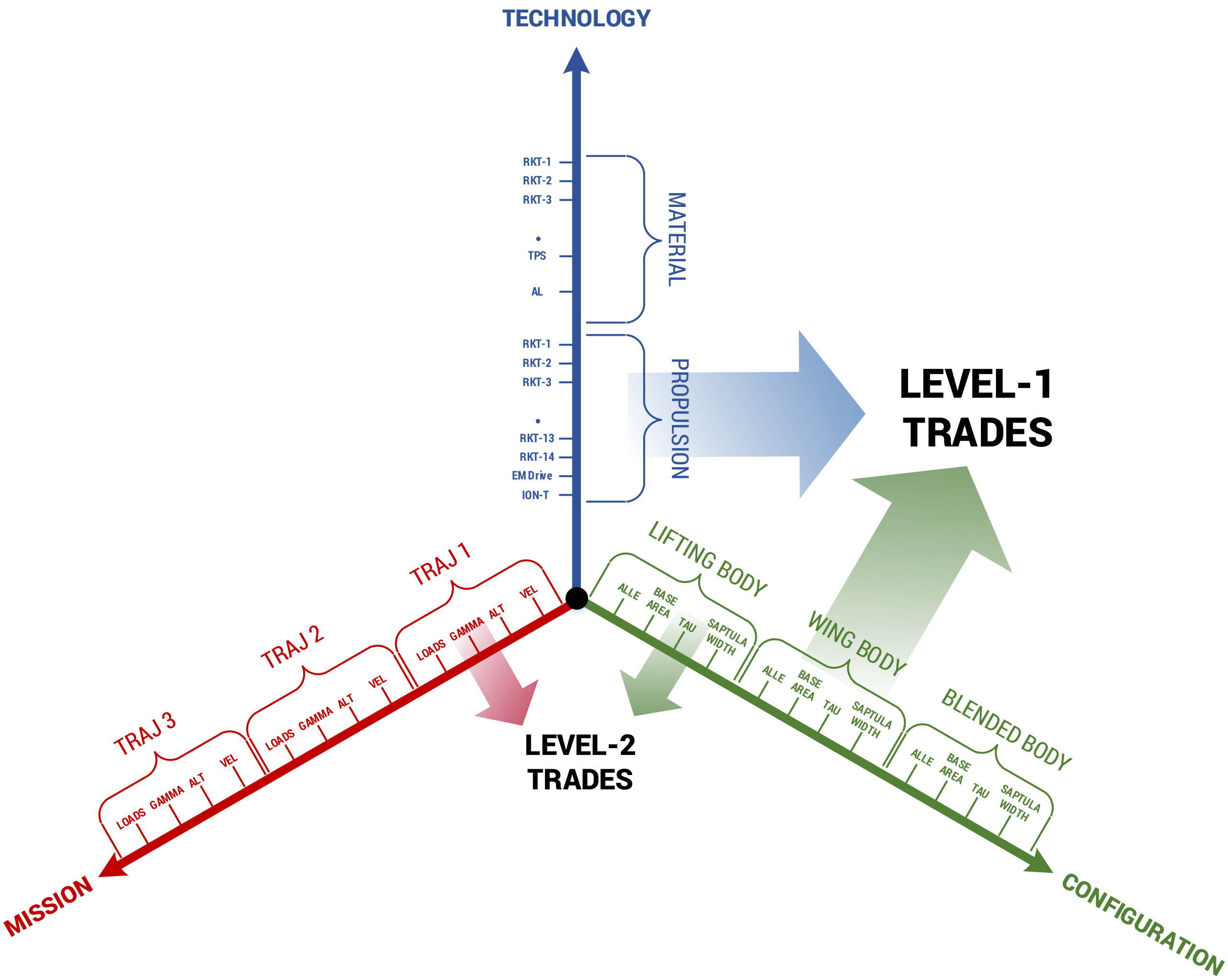

FIGURE 4.2 – Complete overall trade-matrix showing primary and secondary trades

to demonstrate the application of the generic SAS-GDSP solution to the LRV class of the SAVs which lie at hierarchy level-2 of the SAS. Following that is a discussion of the possible trade studies that can be conducted within the LRV realm and identify what are the most significant design drivers that affect the overall design solution.

### 4.1.2 *Overall LRV Design Trade Matrix*

The CD phase is defined as the most abstract design phase because of the information scarce nature[3]. At the beginning of the project, the designer is presented with just the primary objective of the vehicle, thus giving him maximum design freedom for meeting the objectives. At this stage, the design dashboard is the designer's playground where he is free to choose any tools, select any combination of the subsystem

[3] see Figure 1.13 in Section 1.2.1

technology and look for mission capability trades that could lead to even redefine the original mission objectives. A hypothetical example clarifies this notion where the primary mission objective given to the designer is to design a vehicle to for sub-orbital tourism purpose for 2 crew and 4 passenger requirement with technology constraints of using LOX/LH2 rocket propulsion. By conducting a truly comprehensive assessment, the designer might find out that a vehicle with 6 passenger capacity is more cost effective that the vehicle sized only for the original requirements of 4 passengers. Clearly, this type of design capability would enable the decision maker to comprehensively assess all design options stemming from the mission-hardware-technology domain towards better informed decisions. This multi-disciplinary decision making is the primary responsibility of the CD team related to exploring the design trade space across all domains related to the mission.

Based on the above discussion, an extensive amount of trades can be conducted at various levels throughout the CD phase. As a consequence, it becomes important to identify which trades are worth exploring that actually provide the most comprehensive capability for the overall vehicle product. In the present research context, an extensive trade matrix, see Figure 4.34. have been executed. While some trades have been found to show negligible effect on the overall design solution, others do prove to be of significant value. The overall trade matrix required to correctly explore an operational mission usually exceeds to tool and time limitation of the design team. Although such trade matrix does always represent a multi-dimensional domain, it is visualized here as a three dimensional matrix for visualization purpose only in Figure 4.34. The following types of trade categories are thus identified to be of immediate relevance for the current research study:

1. *Level-1 Highest of importance trades:* These define the three primary trade axes of Figure 4.34 that defines the overall trade space. In context of the MDA and the sizing logic, this category represents trades conducted for major design decisions. An example trade would be the selection of the geometric configuration from the LB, WB, or the BB geometry alternatives. The following sub-categories exist at this highest level of the vehicle configuration trade matrix.

   i. Trades for vehicle geometric configuration where several options are applicable for the vehicle class being considered. This includes the overall vehicle configuration (WB vs LB vs BB) for the LRV cases and identifies the overall hardware configuration level design trade space. The primary questions asked here is: "What overall vehicle shape is most beneficial for the given mission objectives?“

  ii. Trades for the subsystems level where several options can be applicable for the primarily constituent components. This primary addresses the level of technology for major design disciplines like type of propulsion system, selection of the material etc. For example, selection of a liquid rocket engine versus a hybrid rocket engine. The primary question addressed in this category is; “ What technology is most beneficial for a subsystem?“
  iii. Mission trade space addresses various mission profiles to find the most optimum trajectory or it identifies the correct primary mission objectives similar to the case discussed in the example above. The primary question asked here is: “What mission profile is most beneficial for the given objectives? “

2. *Level-2 Second of importance trades:* These trades are found secondary in their impact on the overall solution space as they trade on individual parameters under each option of the Level-1 trades. As seen in Figure 4.34, combinations of the different values in the set of geometric parameters (LEA, SPATULA , TAU etc) applicable to one configuration (LB, WB, or BB) results in a specific vehicle shape. For example, among the LB configuration option, the selection of the cross-sectional base area affects the overall geometric properties of the vehicle. A similar logic can be applied to the other two primary trade matrix dimensions.

### 4.1.3 *Application of DBMS in SAS-GDPS*

It is found that the formulation of the primary three dimensional vehicle configuration trade matrix provides a valuable insight that signifies the multi-disciplinary nature of the CD phase assessment and the associated complexity involved. As a consequence, the trade matrix contains a significant amount of combinations and permutations that can be explored at sub-systems and systems level, a sheer quantity of trades which are beyond the scope of this research investigation. In order to effectively explore the design solution space whilst focussing on the most important trades, the AVD Laboratory synthesis capability, the AVD-DBMS, is the choice for the present research investigation. The AVD-DBMS has been included in the review of synthesis systems in Chapter-2, and it is identified as a state-of-the-art Class V synthesis capability. Figure 4.3 presents the schematic that describes how and where the DBMS is utilized within the overall SAS-GDSP methodology.

The four primary System Development Processes[4] are explained in

[4] Four steps of the SAS-GDSP solution defined in Chapter 3 (see Section 3.2):
1. Mission Analysis
2. Technology Requirement
3. Hardware Selection
4. Cost-per-Performance Screening

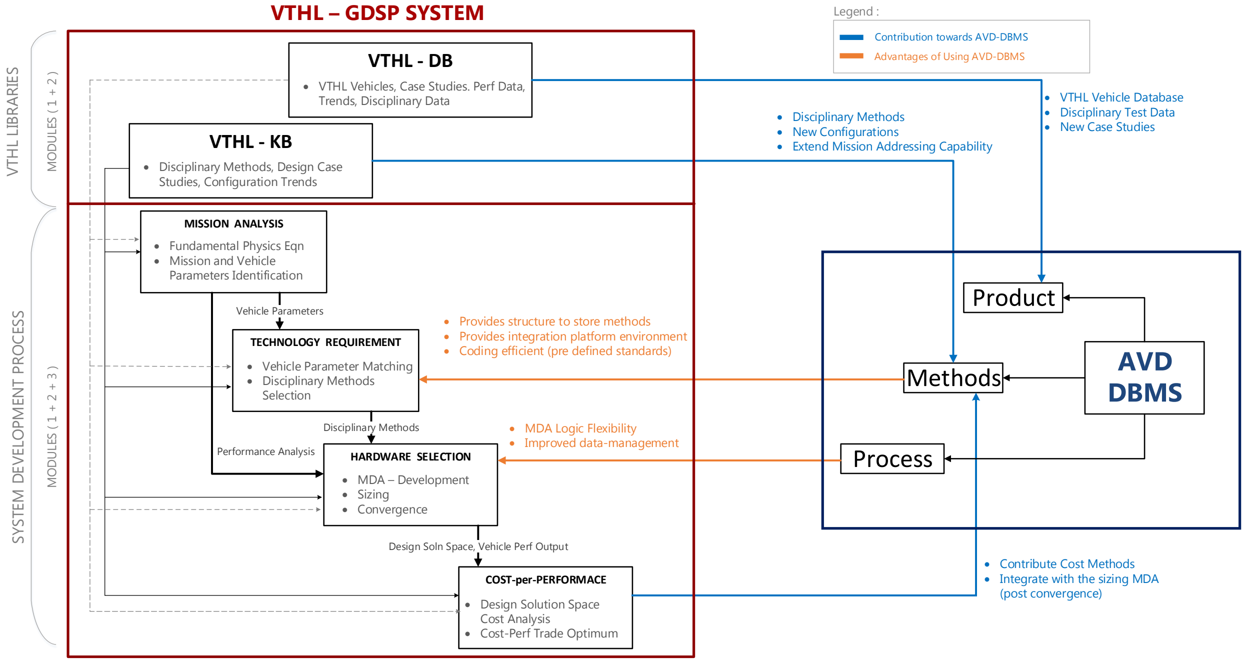

FIGURE 4.3 – Schematic showing the benefits of using the AVD-DBMS for the SAS-GDPS and contributions of the SAS-GDPS towards growth of the DBMS.

Chapter 3 where the *'Technology Requirements'* includes the recognition of the most important discipline parameters and selection of the first order analysis methods solving for the respective parameters. The next step, the *'Hardware Selection'* then represents combinations of primary disciplines into an integrated MDA to develop a sizing framework. The DBMS is applicable towards these two steps in the overall process as it provides a generic platform to store and assemble primary discipline methods into a modular sizing code. The DBMS is a generic platform which assembles a sizing logic by collecting primary constituents of an MDA into a problem specific sizing code. Before the VTHL SAS research study, the DBMS has only been only applied for a hypersonic airbreather demonstrator study conducted as a part of a contract between the AVD LLC. and the USAF hypersonic department[74]. As a consequence, the methods, data, and efficiency of the system has been evolved to only the hypersonic cruise class of vehicles.

Thus, using the generic DBMS kernel for the VTHL SAS research investigation demonstrates the versatility of the DBMS. The application of the DBMS for the present research study also enhances the DBMS discipline method library, and further improves the scope of the system towards its application for future cases of LRV studies. The VTHL SAS specific discipline methods library and MDA adjustments further demonstrate the novel forecasting capability of the system towards a true generic system with the goal of correctly trading permutations of LRV options like single-stage-to-orbit versus two-stage-to-orbit and others. The next section provides an overview of the main features and primary components of the DBMS system.

### 4.1.4 *LRV Case-Studies Selection*

This research investigation applies the proposed generic SAS-GDSP solution through the DBMS system to size two LRV case-studies. This implementation will be demonstrated along the sizing of three case-studies. Each case-study is sized for a fixed LEO reentry mission which enables a consistent comparison amongst the alternatives considered. The case-studies are described as follows;

1. *Verification Case using The Boeing X-20 Dyna-Soar:* The X-20 Dyna-Soar is sized for the purpose of verification and validation of the results generated by the SAS-GDSP.

2. *Generic Case using the Lifting Body:* Exploration of design solution space for the LB configuration is addressed. Selected geometric trades (leading edge sweep, cross section area, spatular width etc.) are executed to explore and visualize the sensitivities of the configuration concept choice as a continuum in the overall design solution space.

3. *Generic Case-2 using the Wing Body:* Exploration of design solution space for the generic WB configuration is executed in this case. The technology trades (engine and fuel types) and geometry trades (three different WB geometry shapes) are executed to observe the effect of technology and geometry trades combinations on the overall design solution space.

The selected LRV case-studies are sized following the four step process of the SAS-GDSP solution concept which is described in the previous Chapter. The '*Mission Analysis*' step is used to analyze an orbital reentry flight path which is common for all three case-studies. The DBMS is engaged for the execution of the next two steps as described earlier. The final step of measuring the '*Cost-per-Performance*' is then used to select the most pertinent design solution category among the generic categories of the Lifting Body solutions.

## 4.2 *DBMS*

The Aerospace Vehicle Design (AVD) Laboratory at the University of Texas at Arlington has recently developed and currently utilizes a proprietary prototype Data Base Management System (DBMS) that provides the unique capability of developing custom-tailored sizing codes

FIGURE 4.4 – Overall breakdown of the system elements in the AVD-DBMS. Reproduced here from Gonzalez[26]

specific to the problem at hand. This section provides an overview description of the DBMS synthesis capability, its primary components and execution process followed by its application for sizing the LRV segment of the VTHL system. This latest incarnation of the AVD Laboratory synthesis methodology and software has been developed through the collaborative research effort of Gonzalez[26], Omoragbon[72] and Oza[11]. Further details of the system and its development process are found in the dissertations of the aforementioned researchers[11, 26, 72].

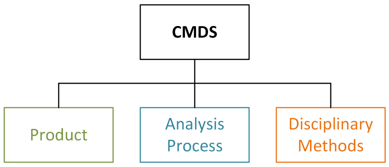

FIGURE 4.5 –

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AVD-DBMS is a special type of CMDS for specific application towards flight vehicle synthesis system. Each of the top-level component is build by using fundamental building blocks:

» Reference Form
» Variable Form
» Tree Structure.

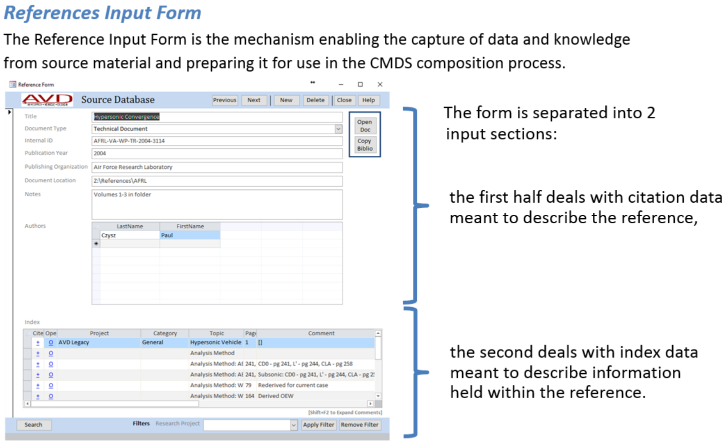
### *4.2.1 DBMS System Overview*

The DBMS is not a design synthesis program in itself, rather, it is a software that creates unique MDA sizing codes. The process is executed in Microsoft ACCESS. The technical reference library, methods library, historical vehicle database, and sizing process architecture database are managed with this system. The physics-based VTHL SAS sizing methodology or MDA is created using this system. The system is primarily executed in three layers, details of which are shown in Figure 4.4. Following description of the DBMS system now provides a brief explanation of the major components and is taken from Gonzalez[26].

*Fundamental Building Blocks*: REFERENCE FORM, VARIABLE FORM, TREE STRUCTURE

The DBMS is fundamentally developed by following the logic of a Complex Multidisciplinary System (CMDS) which is composed of three primary functional information classes, namely; 1) Product, 2)

Analysis Process, and 3) Disciplinary Methods, see Figure 4.5. Each component is made of three types of the building block input mechanisms referred to by Gonzalez as the *utility modules*. These modules are the basic elements through which the user interacts with the system.



**References Input Form**

The Reference Input Form is the mechanism enabling the capture of data and knowledge from source material and preparing it for use in the CMDS composition process.

Title: Hypersonic Convergence
Document Type: Technical Document
Internal ID: AFRL-VA-WP-TR-2004-3114
Publication Year: 2004
Publishing Organization: Air Force Research Laboratory
Document Location: Z:\References\AFRL
Notes: Volumes 1-3 in folder

Authors

| LastName | FirstName |
|---|---|
| Czysz | Paul |

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| ± | O | AVD Legacy | General | Hypersonic Vehicle | 1 | [] |
| ± | O | | | Analysis Method | | |
| ± | O | | | Analysis Method: AE | 241, | CD0 - pg 241, L' - pg 244, CLA - pg 258 |
| ± | O | | | Analysis Method: AE | 241, | Subsonic: CD0 - pg 241, L' - pg 244, CLA - pg 2 |
| ± | O | | | Analysis Method: W | 79 | Rederived for current case |
| ± | O | | | Analysis Method: W | 164 | Derived OEW |

[Shift+F2 to Expand Comments]

Research Project

The form is separated into 2 input sections:

the first half deals with citation data meant to describe the reference,

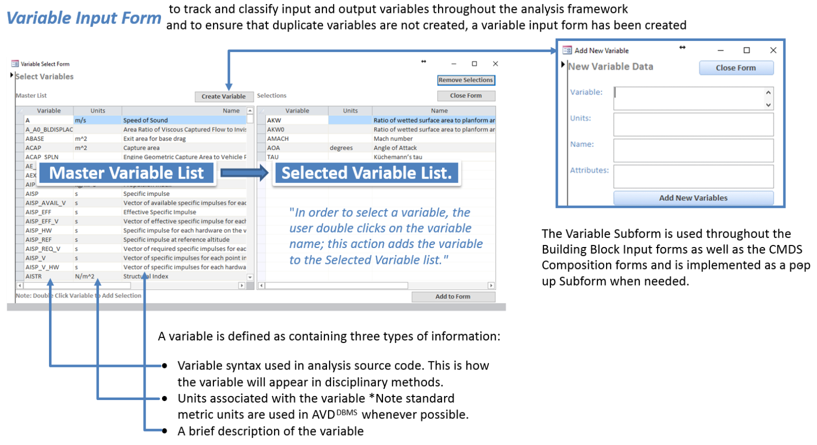
the second deals with index data meant to describe information held within the reference.

FIGURE 4.6 – DBMS Building Block-1: Reference Input Form. Reproduced here from Gonzalez[26]

The first *building block*, the *Reference Input Forms* is used to capture the data and knowledge from the reference source material. Figure 4.6 shows a reference input form from the DBMS and identifies two input sections used to store and index the relevant information that is applied in the system.

The second building block is the *Variable Input Form* that is used to store, track, select and classify input and output variables within the system. This mechanism ensures that duplicate variables are not created within the system and thus provides the ability to manage the variables throughout the analysis framework. Three specific information categories are assigned to each variable, 1) a Unique Syntax that shows how the variable appears in the system, 2) Units associated with each variable (SI unit system is followed), and 3) a brief description of the variable. Figure 4.7 shows the variable input form with description of main segments as they appear in the system.

The third building block mechanism is the *Input Tree Diagrams* which provide a hierarchy structure to rapidly select various options and develop a vehicle, mission, operation or technology assessment. "The Tree View control displays a hierarchical list of Node objects, each of which consists of a label and an optional bitmap. A TreeView is typically used to display the headings in a document, the entries in an index, the files and directories on a disk, or any other kind of information that might usefully be displayed as a hierarchy."[84] Figure4.8 shows the tree structure for its three main application in the system



to track and classify input and output variables throughout the analysis framework and to ensure that duplicate variables are not created, a variable input form has been created

| Variable | Units | Name |
|---|---|---|
| A | m/s | Speed of Sound |
| A_A0_BLDISPLAC | | Area Ratio of Viscous Captured Flow to Invis |
| ABASE | m^2 | Exit area for base drag |
| ACAP | m^2 | Capture area |
| ACAP_SPLN | | Engine Geometric Capture Area to Vehicle F |
| AE_ | | |
| AEX | | |
| AIP | | |
| AISP | s | Specific impulse |
| AISP_AVAIL_V | s | Vector of available specific impulses for eac |
| AISP_EFF | s | Effective Specific Impulse |
| AISP_EFF_V | s | Vector of effective specific impulse for each |
| AISP_HW | s | Specific impulse for each hardware on the v |
| AISP_REF | s | Specific impulse at reference altitude |
| AISP_REQ_V | s | Vector of required specific impulses for eac |
| AISP_V | s | Vector of specific impulses for each point in |
| AISP_V_HW | s | Vector of specific impulses for each hardwa |
| AISTR | N/m^2 | Structural Index |

Note: Double Click Variable to Add Selection

| Variable | Units | Name |
|---|---|---|
| AKW | | Ratio of wetted surface area to planform ar |
| AKW0 | | Ratio of wetted surface area to planform ar |
| AMACH | | Mach number |
| AOA | degrees | Angle of Attack |
| TAU | | Küchemann's tau |

*"In order to select a variable, the user double clicks on the variable name; this action adds the variable to the Selected Variable list."*

The Variable Subform is used throughout the Building Block Input forms as well as the CMDS Composition forms and is implemented as a pop up Subform when needed.

A variable is defined as containing three types of information:

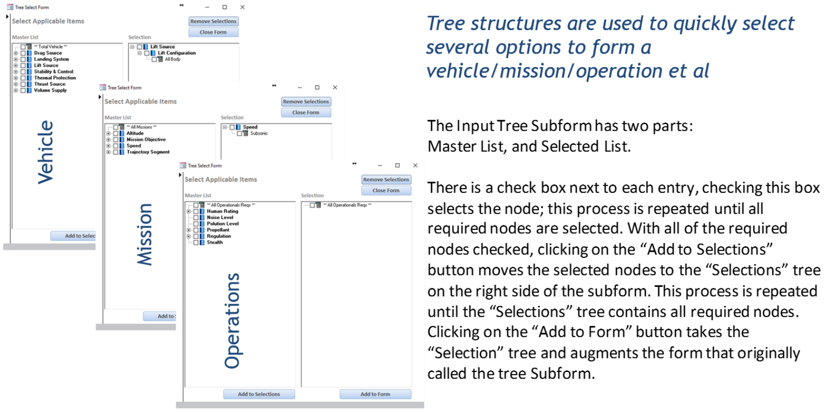
- Variable syntax used in analysis source code. This is how the variable will appear in disciplinary methods.
- Units associated with the variable *Note standard metric units are used in AVD$^{DBMS}$ whenever possible.
- A brief description of the variable

FIGURE 4.7 – DBMS Building Block-2: Variable Input Form. Reproduced here from Gonzalez[26]

and describes the selecting mechanism to form a specific vehicle, mission or operation by selecting several nodes for each.

### *Primary Components: Product, Process, Methods*

The three primary components of a CMDS are discussed with the following which are generated by using the fundamental building blocks. These describe the three separate classes of information necessary to characterize a vehicle synthesis system. Each component is discussed and shown in terms of first, the generic functional information concept it represents, and second the implementation of the concept in the DBMS Access software. The first component is the *Product* which represents the vehicle and is comprised of three parts, namely; 1) Hardware, 2) Operational Events, and 3) Operational Requirements. Figure 4.9 shows an overview of each generic category and what it entails in relation to a flight vehicle.



*Tree structures are used to quickly select several options to form a vehicle/mission/operation et al*

The Input Tree Subform has two parts: Master List, and Selected List.

There is a check box next to each entry, checking this box selects the node; this process is repeated until all required nodes are selected. With all of the required nodes checked, clicking on the "Add to Selections" button moves the selected nodes to the "Selections" tree on the right side of the subform. This process is repeated until the "Selections" tree contains all required nodes. Clicking on the "Add to Form" button takes the "Selection" tree and augments the form that originally called the tree Subform.

FIGURE 4.8 – DBMS Building Block-3: Input Tree Structure. Reproduced here from Gonzalez[26]

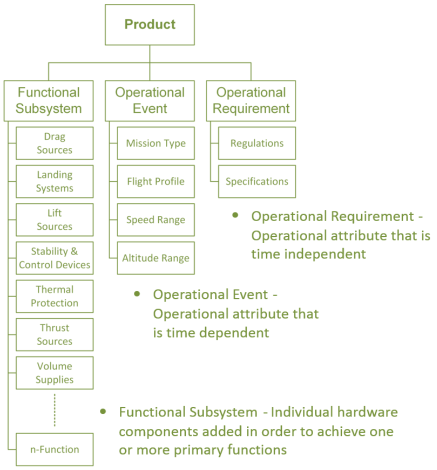
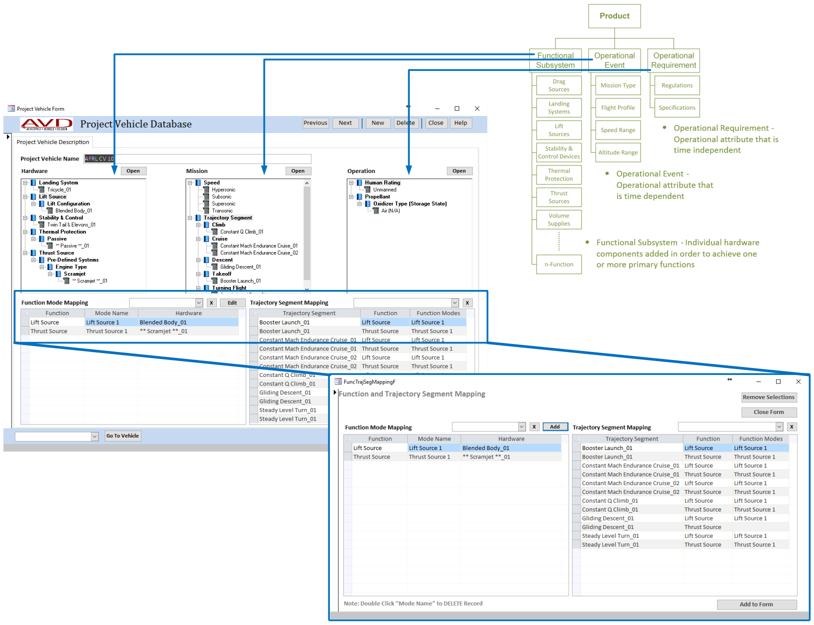


FIGURE 4.9 – Functional Concept of the Primary Component-1: Product. Reproduced here from Gonzalez[26]

Gonzalez[26] defines these three parts as follows:
“*Functional Subsystem* - Individual hardware components added in order to achieve one or more primary functions.
*Operational Event* - Operational attribute that is time dependent.
*Operational Requirement* - Operational attribute that is time independent.“
Figure 4.10 shows the *Product Input Form* as it appears in the DBMS and indicates the associated fields for each constituting part of the product with corresponding generic categories. As shown in the figure, the Hardware, Operational Event, and Operational Requirements input mechanism is done via the *Input Tree subform*. “In addition to the selection of individual components using the *Input Tree subform*, it is also necessary describe the dependencies between the components. Two such relationships are defined using the *Function Mode* and *Trajectory Segment Mapping Subform*“[26], this is shown in the pop-out block in Figure 4.10. The second primary component of the DBMS is the *Analysis Process* and “is defined as any information relating to the overall organization and integration of an Aerospace Synthesis System. The *Analysis Process* is broken into two classes of information: System Elements, and Disciplinary Elements.“[26]. Figure4.11 shows the functional concept of the Analysis Process and the provides the basic description of the constituting categories as defined by Gonzalez[26].

Figure4.12 shows the implementation of the concept breakdown in the MS Access as implemented in the DBMS for each category of the *Analysis Process*. The *System Process Variables* are the most important variables that controls and regulates the flow of the data in the MDA framework. They make up the objective function and are iterated until the objective function is satisfied, thus providing the mathematical convergence proof of the feasibility of the overall solution. The *Disciplinary Variables* are the primary top-level outputs of the involved disciplines. They are regulated by the *Process Variables* for each iteration. Figure4.12 shows the four main windows of the *Analysis Process* where it can be seen that the *Systems Process Variables* are selected in the top-left box and *Objective Function* (Error Function box in bottom left corner of the figure) is made of *System Process Variables*. The box in the middle shows the sequential selection of the primary design disciplines and the box on the top-right corner shows the *Disciplinary Process Variables* for each disciplines. The third and final primary component of the DBMS is the *Disciplinary Method*. Figure 4.13 shows the functional decomposition of this component into three main parts along with the description of each constituent as defined by Gonzalez[26]. This component primarily relates to the ability of the DBMS to handle and store individual disciplinary methods in the system. In order to consistently



- Operational Requirement - Operational attribute that is time independent
- Operational Event - Operational attribute that is time dependent
- Functional Subsystem - Individual hardware components added in order to achieve one or more primary functions

Project Vehicle Name: AFRL CV 10

**Function Mode Mapping**

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

**Trajectory Segment Mapping**

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

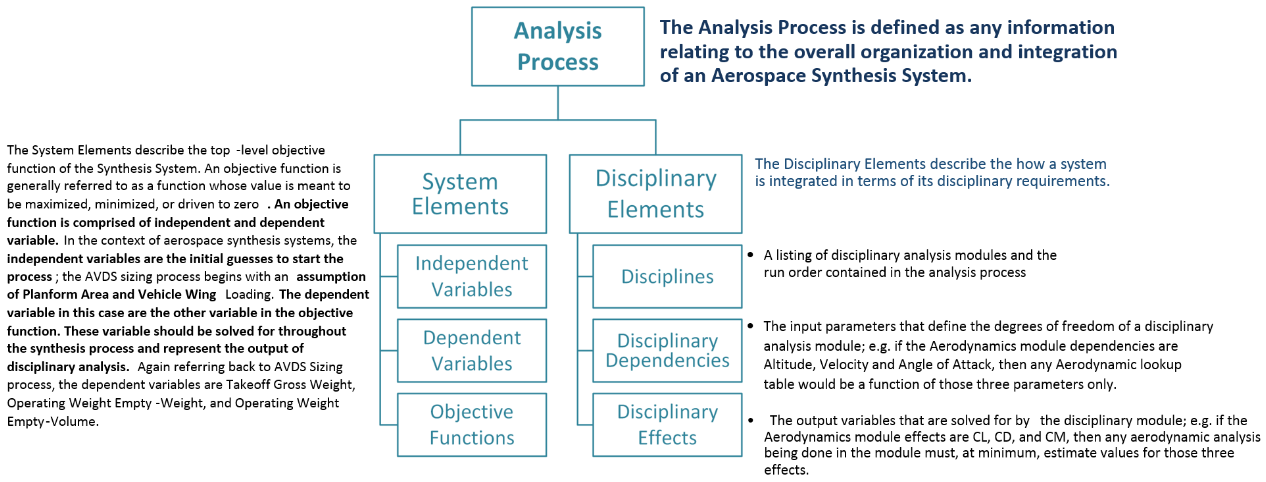
Note: Double Click "Mode Name" to DELETE Record

FIGURE 4.10 – MS Access implementation of the Primary Component-1: Product. Reproduced here from Gonzalez[26]

handle the data flow among the disciplines and to be able to combine the disciplines in the overarching MDA framework defined by the *Analysis Process*, the *Disciplinary Method* is associated to the *Product* component identifying at which product node does the disciplinary method is applied. The *Disciplinary Variables* define the involved variables that the method is made up of and further specify the input and output variables for each method. The *Analysis* part of the *Disciplinary Method* (see Figure 4.13)component contains the system of equations or the empirical data that connects input and output variables.

Figure 4.14 shows the *Disciplinary Methods* form as seen in the MS Access system of the DBMS which manages the three components described above in the functional decomposition. The analysis aspect of the method is stored in an MATLAB file external to the DBMS which contains only the analysis portion of the method using the input, output and internal variables involved in the method's analysis. The input and output variables for each method is defined and associated with the method internally in the DBMS. With this setup, the system acts as patching mechanism that connects disciplines only in terms of the input/output variables among various disciplines while not being influenced by the analysis implementation.

This marks the end of the discussion of the primary components of the DBMS system which represents the fundamental kernel thus building blocks for a synthesis system. By following a warehouse type analogy the DBMS selects various building blocks and assembles



**The Analysis Process is defined as any information relating to the overall organization and integration of an Aerospace Synthesis System.**

The System Elements describe the top -level objective function of the Synthesis System. An objective function is generally referred to as a function whose value is meant to be maximized, minimized, or driven to zero **. An objective function is comprised of independent and dependent variable.** In the context of aerospace synthesis systems, the **independent variables are the initial guesses to start the process** ; the AVDS sizing process begins with an **assumption of Planform Area and Vehicle Wing** Loading. **The dependent variable in this case are the other variable in the objective function. These variable should be solved for throughout the synthesis process and represent the output of disciplinary analysis.** Again referring back to AVDS Sizing process, the dependent variables are Takeoff Gross Weight, Operating Weight Empty -Weight, and Operating Weight Empty-Volume.

The Disciplinary Elements describe the how a system is integrated in terms of its disciplinary requirements.

- A listing of disciplinary analysis modules and the run order contained in the analysis process
- The input parameters that define the degrees of freedom of a disciplinary analysis module; e.g. if the Aerodynamics module dependencies are Altitude, Velocity and Angle of Attack, then any Aerodynamic lookup table would be a function of those three parameters only.
- The output variables that are solved for by the disciplinary module; e.g. if the Aerodynamics module effects are CL, CD, and CM, then any aerodynamic analysis being done in the module must, at minimum, estimate values for those three effects.

FIGURE 4.11 – Functional Concept of the Primary Component-2: Analysis Process. Reproduced here from Gonzalez[26]

them together based on problem specific requirements to custom build unique sizing codes for every problem. This is a fundamentally new approach of addressing flight vehicle sizing in a MDA framework during the CD phase assessment and provides enhanced control over the creation of custom-tailored sizing codes unique to the specific problem at hand. This ability is found to be especially advantageous in exploring the overall trade matrix which has been explained earlier in Section 4.1 as the modular nature gives the designer a superior control over individual building blocks and ability to switch or trade where required.

### 4.2.2 *Execution of the DBMS to develop Customized Sizing Codes*

The DBMS system is assembled and managed in the MS Access where it is executed in four sequential steps to finally create a custom flight vehicle sizing code. The four executable steps are, 1) Matching, 2) Selecting, 3) Arranging, and 4) Generation. All four steps are implemented in the DMBS through an *Input Form Mechanism* where the primary top-components, *Product, Analysis Process and Disciplinary Methods* are combined in a step-wise manner. The four steps makes sure that the parametric connections and the data-structure is formulated correctly. At the end of the fourth step, *Generation*, the DBMS produces a sizing code which is a custom tailored and stitched form of disciplinary methods MATLAB files that are connected via the parametric connections defined in the DBMS.

The process of creating a synthesis sizing code begins by initiating a new architecture. The first step is the *Matching* step where the vehicle's hardware, mission and operations are specified by selecting a prede-

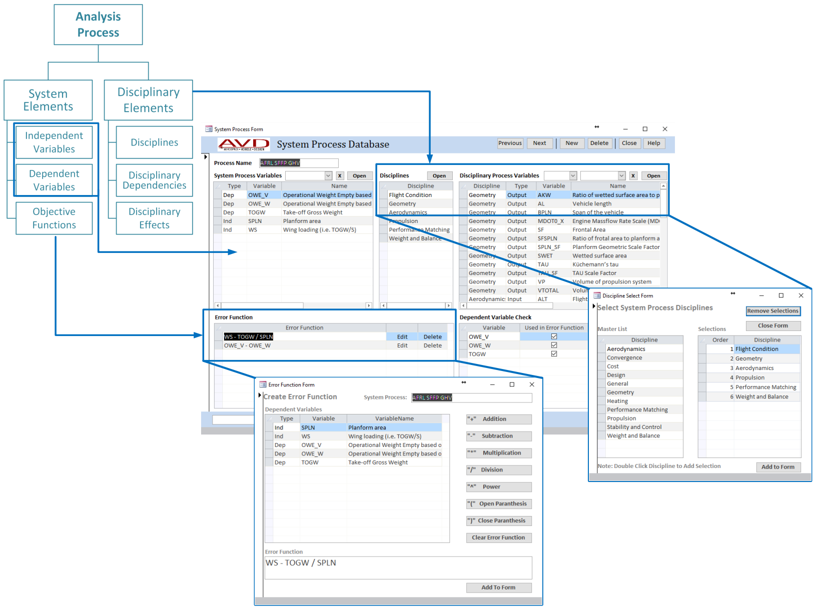
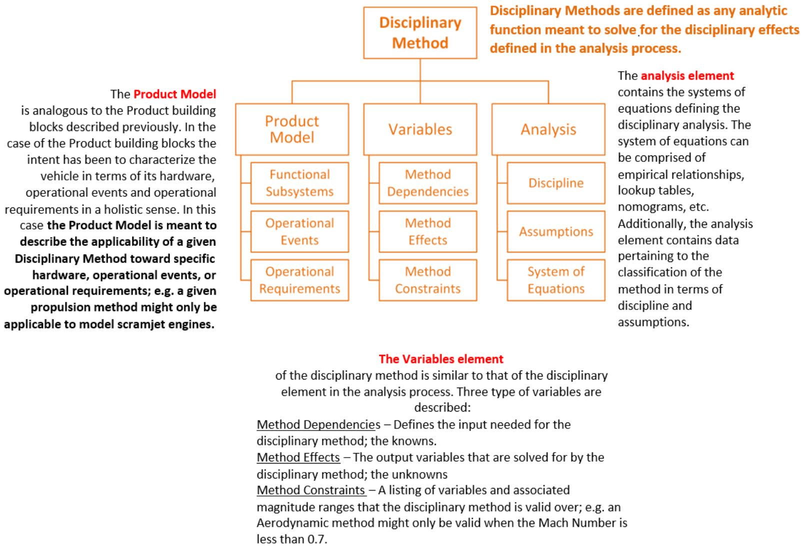


FIGURE 4.12 – MS Access implementaion of the Primary Component-2: Analysis Process. Reproduced here from Gonzalez[26]

fined product. Also a part of the *Matching* step is the selection of the *Analysis Process*, which is selected from a predefined template. Once the vehicle and analysis process template are chosen, the next step provides the user with a list of disciplinary methods which produce the output variables as required in the Analysis Process variables. This is a user dependent step where the user has to make sure that the methods chosen are consistent with the vehicle and analysis process. For this study, the methods have been created specific to the architectures and so are created by the user.

Once the methods are selected for each design discipline, the DBMS moves to the next step, *Arranging*, where the trajectory segments are asked to be placed in the sequence of mission profile. This sequence stitches the performance methods in a sequence such that the total weight ratio and fuel fraction for the entire mission trajectory can be calculated. Also the *Arranging* step makes sure that no two methods are being executed for the same flight phase for the same disciplines and thus provides user with option to specify the filter for how and where each method must be executed. This is specifically done for the Aerodynamic methods where the methods specific to the Mach number range are assigned.

The *Generation* step is the next and last step of the process where a variable based check is implemented for the entire product arrangement, disciplinary methods and variables such that no inconsistent variable selection happens. Once this check is found to be satisfied,



**Disciplinary Methods are defined as any analytic function meant to solve for the disciplinary effects defined in the analysis process.**

The **Product Model** is analogous to the Product building blocks described previously. In the case of the Product building blocks the intent has been to characterize the vehicle in terms of its hardware, operational events and operational requirements in a holistic sense. In this case **the Product Model is meant to describe the applicability of a given Disciplinary Method toward specific hardware, operational events, or operational requirements; e.g. a given propulsion method might only be applicable to model scramjet engines.**

The **analysis element** contains the systems of equations defining the disciplinary analysis. The system of equations can be comprised of empirical relationships, lookup tables, nomograms, etc. Additionally, the analysis element contains data pertaining to the classification of the method in terms of discipline and assumptions.

**The Variables element** of the disciplinary method is similar to that of the disciplinary element in the analysis process. Three type of variables are described:

Method Dependencies – Defines the input needed for the disciplinary method; the knowns.

Method Effects – The output variables that are solved for by the disciplinary method; the unknowns

Method Constraints – A listing of variables and associated magnitude ranges that the disciplinary method is valid over; e.g. an Aerodynamic method might only be valid when the Mach Number is less than 0.7.

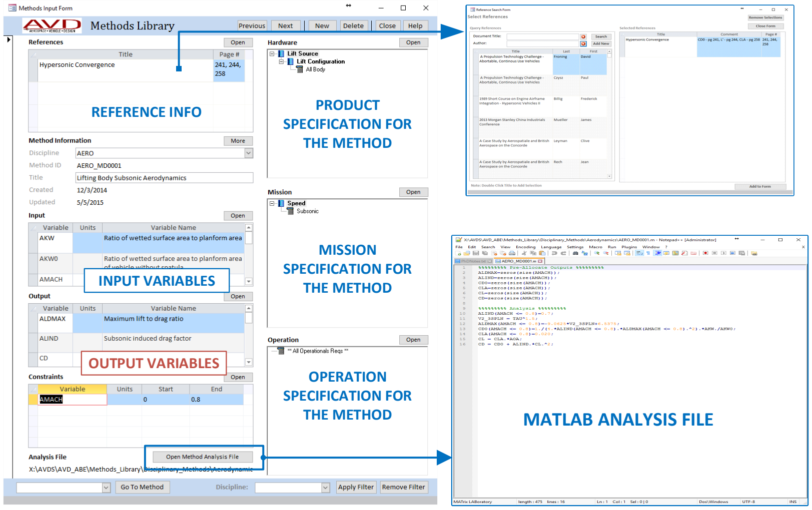
FIGURE 4.13 – Functional Concept of the Primary Component-3: Methods. Reproduced here from Gonzalez[26]

the DBMS has arranged all the disciplinary variables in a sequential order of execution following the logic defined in the Analysis Process for each disciplines. At the end of this step, the system selects the MATLAB analysis files for each disciplines that are stored on a server space and stitches them together in the variable execution logic defined in the MS Access system. Thus the final MATLAB based flight vehicle sizing code is generated. User now needs to input the required disciplinary values as demanded by the disciplinary methods. The overall execution process is presented here in Figure 4.15 in the Nassi-Schnidermann diagram format which shows specific instructions for each execution step. In addition to the process flow, a systems architecture map is produced by McCall (AVD member) that specifies each step and its primary constituent components, see Figure 4.16.

## 4.3 SAV Physical Solution Architecture

Following the description of the DBMS platform, this section provides specific details of the four System Development Processes (SDPs) of the SAS-GDSP. The logical description of these four steps and their specific outputs have been described earlier in Chapter 3[5]. The four sequential SDPs in the order of their execution are as follows; 1) Mission Analysis, 2) Technology Requirement, 3) Hardware Selection and 4) Cost-per-Performance Solution Space. It must be noted that while the logical description of the four steps is generic in nature and hence in theory could be applied to any SAV or SAS, the following description of each

[5] See Section , Figure



**References**

| Title | Page # |
|---|---|
| Hypersonic Convergence | 241, 244, 258 |

**Method Information**

Discipline: AERO
Method ID: AERO_MD0001
Title: Lifting Body Subsonic Aerodynamics
Created: 12/3/2014
Updated: 5/5/2015

**Input**

| Variable | Units | Variable Name |
|---|---|---|
| AKW | | Ratio of wetted surface area to planform area |
| AKW0 | | Ratio of wetted surface area to planform area of vehicle without spatula |
| AMACH | | |

**Output**

| Variable | Units | Variable Name |
|---|---|---|
| ALDMAX | | Maximum lift to drag ratio |
| ALIND | | Subsonic induced drag factor |
| CD | | |

**Constraints**

| Variable | Units | Start | End |
|---|---|---|---|
| AMACH | | 0 | 0.8 |

**Analysis File**
X:\AVDS\AVD_ABE\Methods_Library\Disciplinary_Methods\Aerodynamic

**Hardware**
Lift Source
Lift Configuration
All Body

**Mission**
Speed
Subsonic

**Operation**
** All Operationals Reqs **

Note: Double Click Title to Add Selection

X:\AVDS\AVD_ABE\Methods_Library\Disciplinary_Methods\Aerodynamics\AERO_MD0001.m - Notepad++ [Administrator]

```
%%%%%%%%%% Pre-Allocate Outputs %%%%%%%%%%
ALDMAX=zeros(size(AMACH));
ALIND=zeros(size(AMACH));
CD0=zeros(size(AMACH));
CLA=zeros(size(AMACH));
CL=zeros(size(AMACH));
CD=zeros(size(AMACH));

%%%%%%%%%% Analysis %%%%%%%%%%
ALIND(AMACH <= 0.8)=0.7;
V2_SSPLN = TAU^1.5;
ALDMAX(AMACH <= 0.8)=-9.0625*V2_SSPLN+6.5375;
CD0(AMACH <= 0.8)=1./(4.*ALIND(AMACH <= 0.8).*ALDMAX(AMACH <= 0.8).^2).*AKW./AKW0;
CLA(AMACH <= 0.8)=0.020;
CL = CLA.*AOA;
CD = CD0 + ALIND.*CL.^2;
```

MATrix LABoratory length : 475 lines : 16 Ln : 1 Col : 1 Sel : 0 | 0 Dos\Windows UTF-8 INS

FIGURE 4.14 – MS Access implementaion of the Primary Component-3: Methods. Reproduced here from Gonzalez[26]

step is specific to the LRV case. Clearly, the equations, methods, and analysis explained below represent a specific application of the four generic steps and would be different in case these steps are applied to another class of flight vehicle or system, like a transonic or supersonic aircraft.

### 4.3.1 *Mission Analysis*

This process addresses a generic mission profile for a LRV system and models the equations depicting critical trajectory phases. The equations derive a physical model that is composed of "*Vehicle Parameter*" and "*Trajectory Parameters*". The emphasis here is to identify the vehicle design parameters and intermediate relationship between Vehicle and Physical parameters which dictates the Trajectory Parameters. Several noted authors like Low[85], Vinh[86], Miele[87], Galman[88] et al. describe the mathematical setup to characterize the physical model for a reentry mission profile and equations setup derived here is based on these. It can be seen that the same parametric and physical affects can be quantified in several ways, depending on the initial parameter selection. For example, while one designer would use reentry velocity as the primary variable to setup a performance equation, the other could use a ratio of reentry velocity to satellite velocity to derive the same performance equation but in a slightly different form. To this effect, the intention here is to use the simpler form of the equation and hence a composite mathematical setup is assembled, as follows.

#### Reentry Flight Path: Orbit to Horizontal Landing

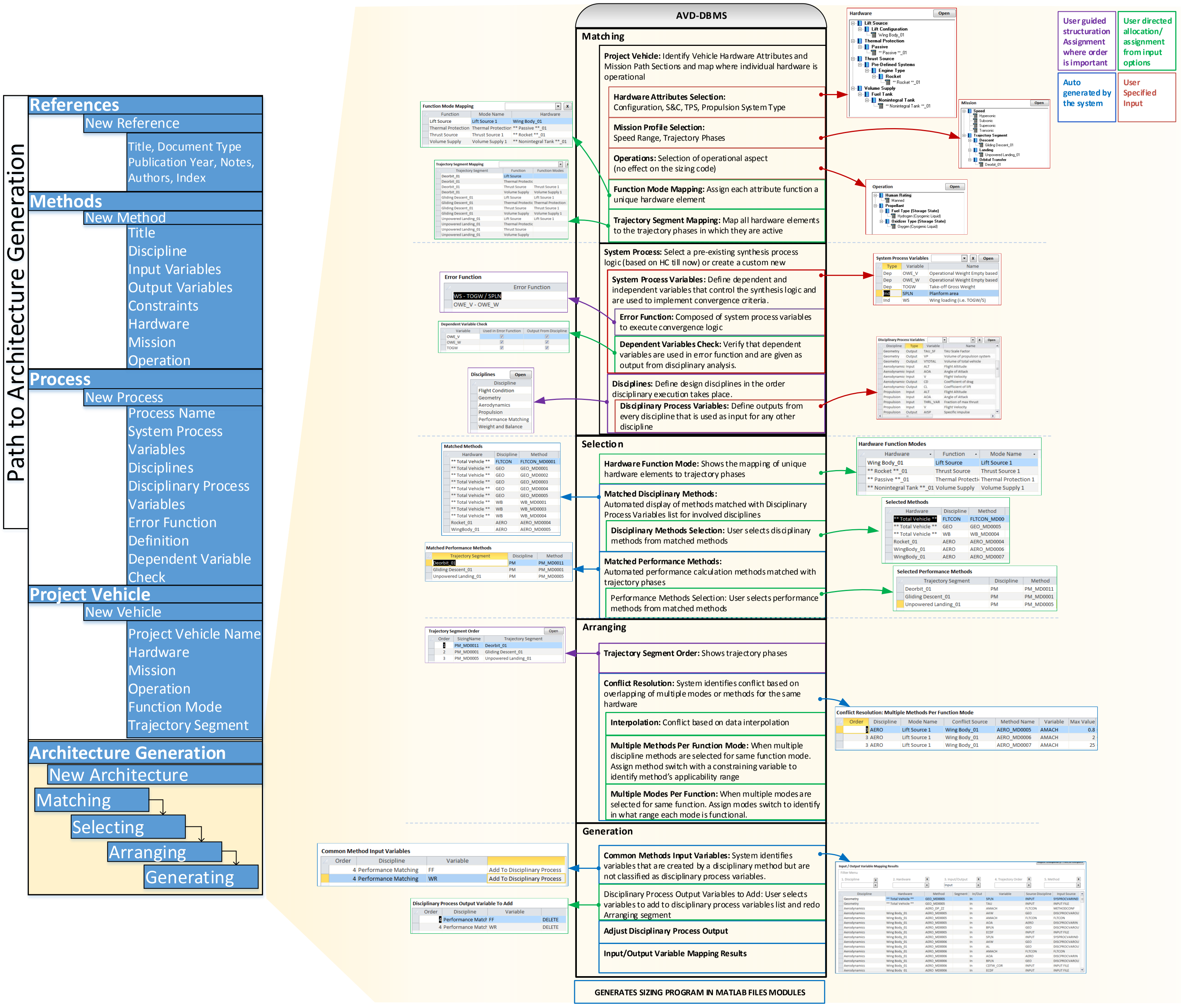


FIGURE 4.15 –
Execution process flow in the DBMS.

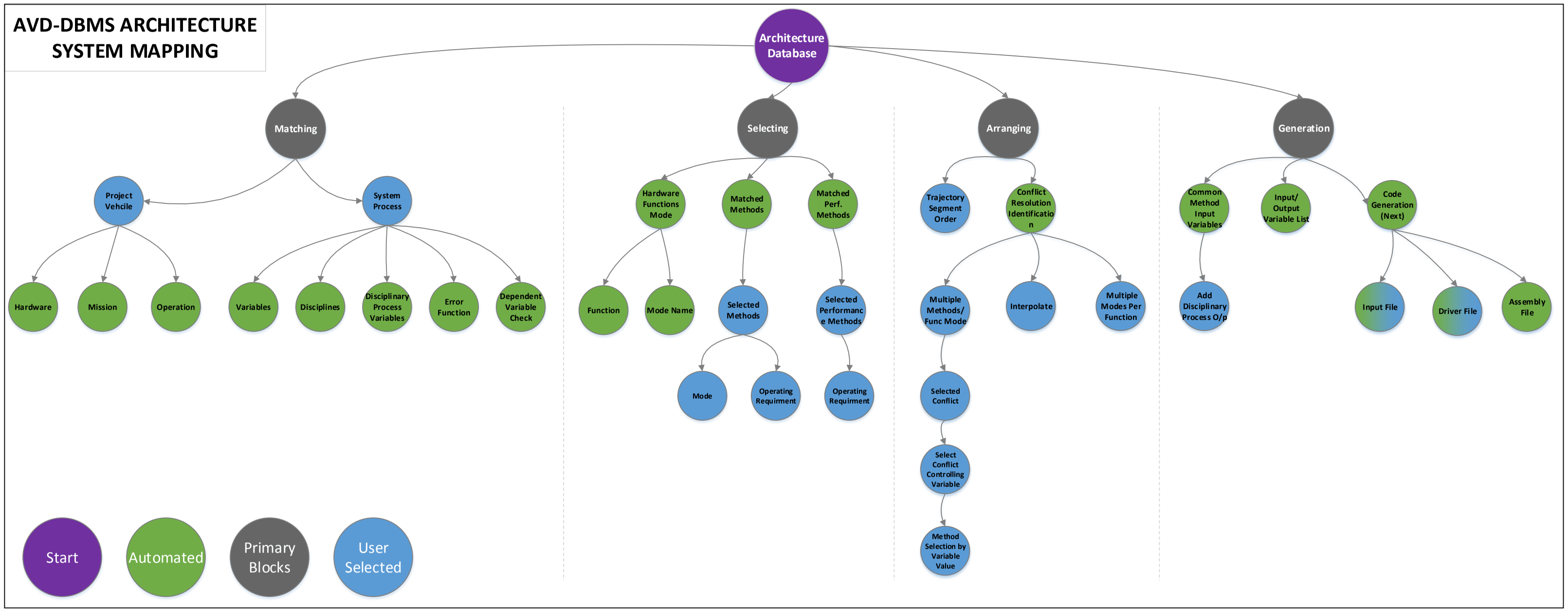
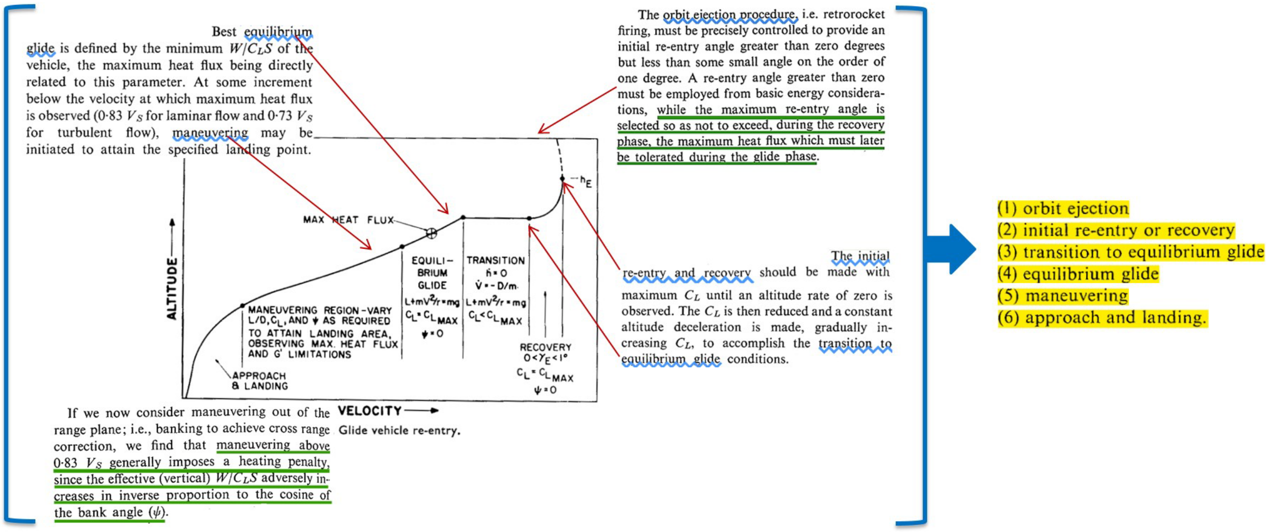


FIGURE 4.16 –
This systems architecture map was created by McCall in an AVD internal study. The map identifies automation characteristics of each module and the various layers of systems elements in the DBMS.



Glide vehicle re-entry.

Best equilibrium glide is defined by the minimum $W/C_LS$ of the vehicle, the maximum heat flux being directly related to this parameter. At some increment below the velocity at which maximum heat flux is observed ($0{\cdot}83\ V_S$ for laminar flow and $0{\cdot}73\ V_S$ for turbulent flow), maneuvering may be initiated to attain the specified landing point.

The orbit ejection procedure, i.e. retrorocket firing, must be precisely controlled to provide an initial re-entry angle greater than zero degrees but less than some small angle on the order of one degree. A re-entry angle greater than zero must be employed from basic energy considerations, while the maximum re-entry angle is selected so as not to exceed, during the recovery phase, the maximum heat flux which must later be tolerated during the glide phase.

The initial re-entry and recovery should be made with maximum $C_L$ until an altitude rate of zero is observed. The $C_L$ is then reduced and a constant altitude deceleration is made, gradually increasing $C_L$, to accomplish the transition to equilibrium glide conditions.

If we now consider maneuvering out of the range plane; i.e., banking to achieve cross range correction, we find that maneuvering above $0{\cdot}83\ V_S$ generally imposes a heating penalty, since the effective (vertical) $W/C_LS$ adversely increases in inverse proportion to the cosine of the bank angle ($\psi$).

(1) orbit ejection
(2) initial re-entry or recovery
(3) transition to equilibrium glide
(4) equilibrium glide
(5) maneuvering
(6) approach and landing.

FIGURE 4.17 – A generic reentry profile mission path with main characteristic features of each segment. The description and figure are reproduced from Galman[88]

Reentry is a crucial section of the mission profile in determining the vehicle system configuration and involved subsystems. Galman[88] provides a composite path to analyze reentry from orbit to landing for lifting reentry vehicles. The entire reentry trajectory is divided in distinct phases, as follows:

- Orbit Ejection
- Initial re-entry
- Transition to Equilibrium Glide
- Equilibrium Glide
- Maneuvering
- Approach and Landing

Figure 4.17 shows the overall description of the generic mission path for a reentry trajectory. The text shows describes the primary physical characteristics specific to each phase is reproduced here from Galman. What follows now is the equations setup that provide a mathematical parametric model for each section. The equations are taken from various literature sources as mentioned above.

*Orbit Ejection to Initial Re-entry*

A vehicle in a circular satellite orbit at altitude $r_s$ has orbital velocity $V_s$, given by:

$$V_s = \sqrt{\frac{\mu}{r_s}} \tag{4.1}$$

This velocity is a measure of vehicle's total kinetic energy, which has to be completely dissipated before landing, usually in form of total heat encountered by the vehicle over the full course of the reentry trajectory. The mission profile phase from orbit ejection to initial reentry, is the flight path traversed by the vehicle in the region above the atmosphere and is analyzed using Kapelerian orbit mechanics. This region does not involves any drag effects and hence no heating issues are addressed.

For a low-circular orbit(LEO), orbit ejection is performed in form of a de-orbit burn by imparting an instantaneous velocity decrements, $V_i$ in a direction directly opposing the orbital velocity. This decrement, $V_i$, depends on the conditions desired at the initial re-entry point in terms of flight path angle and altitude at re-entry point. These initial re-entry conditions determine the nature of flight profile in the atmospheric region, which is the most crucial phase of the trajectory and is discussed further under equilibrium glide. If the entry conditions $(Alt_e, V_e$ and $\gamma_e)$ are fixed, the delta-V required to initiate the reentry is computed through the methods provided by Vinh[86] and Low[85]. First, the conditions after the maneuver are computed as:

$$V_1^2 = V_e^2 + 2\mu\,(\frac{1}{r_s} - \frac{1}{r_e}) \tag{4.2}$$

$$\cos(\gamma_1) = \frac{V_e r_e \cos(\gamma_e)}{V_1 r_s} \tag{4.3}$$

The delta-V is then determined as

$$\Delta V^2 = V_s^2 + V_1^2 - 2V_s V_1 \cos(\gamma_1) \tag{4.4}$$

Generally accepted standard is to use $\gamma_1 = 0$, leading to a tangential reentry burn. The reentry velocity and, the imparted deburn Delta-V magnitude depends on the orbital altitude. Thus, a vehicle approaching from a higher orbit would reenter at higher speeds and thus would encounter similar reentry conditions at higher altitude. For a given reentry altitude, the minimum $V_i$ is indicated at $\gamma_e$ = 0 degrees, while the required Delta-V increases if reentry is performed at a lower altitude as the atmospheric density increases. Figure 4.18 shows variation of Delta-V requirement against reentry flight path angle $\gamma_e$ for different orbital and reentry altitudes.

### *Initial Reentry and Transition to Equilibrium Glide*

The orbit ejection phase is followed by the recovery phase, also called as initial re-entry. It does characterizes conditions before the vehicle enters the atmosphere assuming the equilibrium glide. During

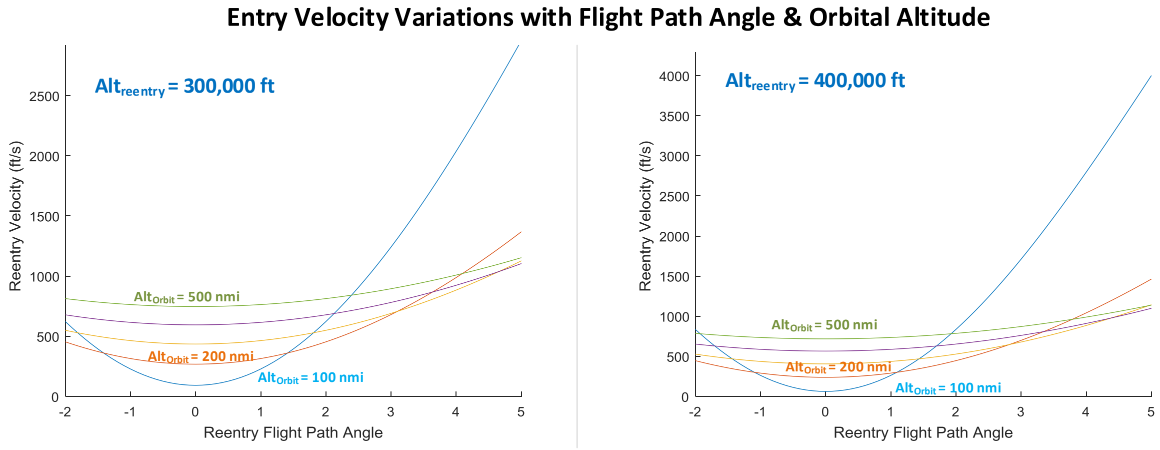


FIGURE 4.18 – The reentry velocity depends on the entry altitude, entry flight path angle and the initial orbital altitude. When reentring from a higher orbital altitude, the reentry velocity increases for a fixed reentry altitude. While, the minimum reentry velocity required to not skip is seen at $\gamma = 0$ independent of the orbital and reentry altitude. The Delta-V then is representative of the retro-rocket used to initiate the deorbit burn.

the initial reentry or recovery phase, the local radius of curvature of flight path is found using the following equation by Galman[88]:

$$r_o = \frac{V_e^2}{g}\left(\frac{\frac{\rho V_e^2}{2}}{\eta} - 1\right)^{-1} \tag{4.5}$$

where, parameter $\eta = \frac{W}{C_L S_{ref}}$ is called as vehicle parameter or lift loading coefficient, and relates to other significant vehicle design parameters, ballistic coefficient, $\beta$ and L/D as follows[6]:

$$\beta = \frac{E}{C_D S_{ref}} = \text{Ballistic Coefficient} \tag{4.6}$$

$$\eta = \frac{W}{C_L S_{ref}} = \text{Lift Loading Coefficient} \tag{4.7}$$

$$\frac{\beta}{(L/D)} = \eta \tag{4.8}$$

The heating effects become dominant during recovery phase, as maximum heat flux depends on the vehicle parameter $\frac{W}{C_L S_{ref}}$ and is independent of L/D. It is due to this reason that recovery is made with max $C_L$. Although, maximum heat flux and deceleration loads experienced during the recovery, the loads are not restrictive to the design variables as these conditions are exceeded in the equilibrium glide phase and are discussed further in next phase. Transition from the recovery phase to the equilibrium phase is to be made by reducing $C_L$ and maintaining constant altitude flight path. This is done to avoid the vehicle from following a skipping trajectory. The following equations describe the transition to equilibrium glide mode.

---

[6] $\eta$ and $\beta$ essentially describe the same physical aspect of the vehicles. While $\beta$ is used more prominently for ballistic vehicles, $\eta$ is more prominent for the lifting vehicles

$$\dot{h} = 0 \tag{4.9}$$

$$\dot{V} = \frac{-D}{m} \tag{4.10}$$

*Equilibrium Glide*

Following the transition from the initial re-entry recovery phase, the vehicle can be commanded to execute a gliding decent or a follow a skip-path depending on the conditions targeted at the beginning of the recovery phase. Since the skip phase is subjected to higher heat flux, a simplified glide path is considered here. The equilibrium glide path represents the conditions where the vehicle's lift and centrifugal forces balance the gravity force. Consequently, this is characterized by small flight path angle, $(-2 << \gamma << 2)$ and negligible time rate change of flight path angle $(\dot{\gamma} = 0)$.

This phase provides calculations for the major performance variables for the overall reentry path as the maximum flight path is traversed in this phase. Additionally the vehicle experiences maximum heat flux in this glide phase and thus the constraints applied to this phase overcomes the heating constraints in the recovery phase.

The equilibrium glide velocity is calculated as a function of altitude and $\eta$ as:

$$V_{eq} = \sqrt{\frac{g\, R_{earth}}{1 + \frac{g\, R_{earth}\, \rho\, h}{2(W/C_L\, S_{ref})}}} \tag{4.11}$$

Acceleration along the glide path is found using following relation:

$$|a| = \frac{g(1 - \bar{V}^2)}{L/D} \tag{4.12}$$

$$\text{where,} \bar{V} = \frac{V_{eq}}{\sqrt{g\, R_{earth}}} \tag{4.13}$$

and glide time is :

$$t_{glide} = \frac{1}{2}\sqrt{\frac{R_{earth}}{g}}\, (L/D)\, ln\left[\frac{1 + \bar{V}_e}{1 - \bar{V}_e}\frac{1 + \bar{V}}{1 + \bar{V}}\right] \tag{4.14}$$

$$\text{where,} \bar{V}_e = \frac{V_{entry}}{\sqrt{g\, R_{earth}}} \tag{4.15}$$

downrange is given by:

$$Range_{glide} = \frac{1}{2}\, (L/D)\, ln\left[\frac{1 - \bar{V}^2}{1 - \bar{V_e}^2}\right] \tag{4.16}$$

The cross range calculation is done by following the approach provided by Vinh[86] which is based on a close approximation formula first given by Eggers[20]:

$$CrossRange_{glide} = \frac{(L/D)^2(\pi^2)}{48} sin(2\sigma) \tag{4.17}$$

where $\sigma$ is the bank angle, which for the above equation is optimum at 45 degrees. Vinh uses above equation to determine a more complicated function which uses a power series expression to solve for optimum bank angle.

*Approach and Landing* The approach and landing phase is dominated by the maneuvering capability of the vehicle. The primary performance measure of interest in this flight phase is the landing velocity which is given by Galman by following equation:

$$V_{landing} = \sqrt{\frac{2}{\rho}\,(W/C_L S_{ref})} \tag{4.18}$$

### PRIMARY DESIGN DRIVERS

With the above equation sequence, it can be seen that the most significant design variables that are representative of the physical characteristics of the vehicle are the Lift Loading Coefficient $\eta$, and vehicle's lift-to-drag ratio (L/D)

$$\text{Lift Loading Coefficient} : \eta = \frac{W}{C_L S_{ref}} \tag{4.19}$$

The $\eta$ is a composite function that is representative of total vehicle weight, lift coefficient and planform area. This identifies following primary design disciplines for involved parameters as;

- Vehicle's Geometric Configuration: $\S_{ref}$
- Aerodynamics: L/D
- Structure and Weight: W

Additionally, the on-board propulsion system is used to perform deorbit burn from the orbital altitude to the reentry altitude. The deorbit burn measure is dependent of the choice of orbital and reentry parameters as shown in the Figure 4.18 earleir in this section.

### SELECTING MODEL MISSION FOR THE CASE-STUDIES

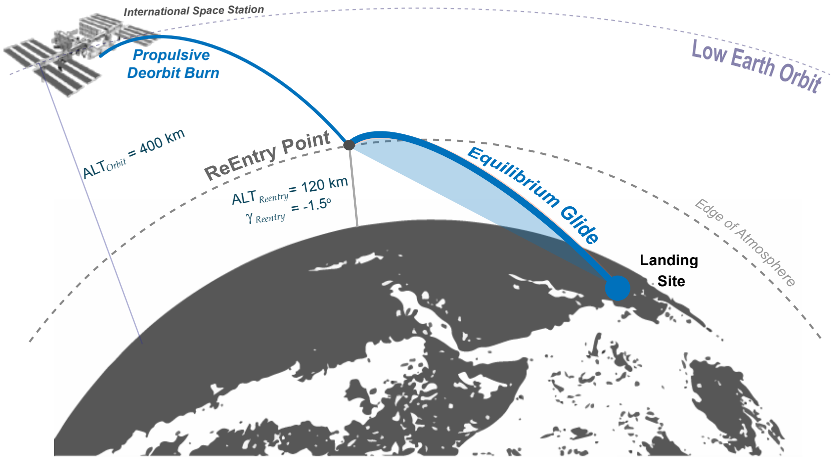


FIGURE 4.19 – Simplified reentry mission profile selected for sizing the LRV case-studies. The Deorbit and Equilibrium glide paths are the most significant phases that cover the overall performance and constraints implementation for the entire mission trajectory.

With the above discussion of the main mission phases, it can be seen that the equilibrium glide phase is the most significant portion of the overall flight profile as most of the performance and constraint parameters are primarily calculated in this section. Based on this logic, a simplified mission profile is selected here which is used for the LRV case-studies. Only the deorbit and equilibrium glide paths are calculated in the performance analysis as they are the two most significant segments that impact the overall vehicle's performance and constraints. The mission selected for the case-studies is a notional ISS resupply mission. The LRV case-studies thus execute a deorbit burn from the orbital altitude of the ISS (400 km) and enters the Earth's atmosphere at an altitude of 120 km. The entry flight path angle at this point is assumed to be -1.5 degrees. The mission objective is to carry a minimum payload of 450 kg ( 1000 lb) and 1 crew member. The selected mission profile and mission path values are shown in the Figure 4.19.

The design variables identified in this first step are used to determine the primary design disciplines. The disciplines are then solved for major disciplinary variables which are essential for sizing the vehicle. The disciplinary analysis methods solving for these primary variables are described next.

### 4.3.2 *Technology Requirement*

This section is tasked to provide a match for a range of design parameters amongst the primary design disciplines. Following then the appropriate disciplinary methods are selected that results in calculation of primary design driving parameters. The disciplinary methods are derived from the knowledge block of the $\text{VTHL}_{\text{KB}}$ and has been manually coded in MATLAB. The variable selection and matching of methods is handled by the AVD-DBMS system. The disciplinary methods and their respective input/output variables are stored in the Disciplinary Methods component of the DBMS and are selected in the Analysis Process component of the DBMS platform for sizing the LRV case-studies. Following five primary disciplines are selected for sizing the LRV case-studies;

1. *Geometry:* Calculates the overall geometric properties of the vehicle. Methods used range from the analytical geometric relations of standard shapes (cone, cylinder, ellipse etc), empirical geometric relations and trends form established studies like Hypersonic Convergence[89] and empirically derived parametric geometries using geometry modeling tools like NASA OpenVSP[7].
2. *Aerodynamics:* Calculation of primary aerodynamic coefficients ($C_L$, $C_D$, L/D etc) for subsonic, supersonic and hypersonic flight regime based on empirical data derived for already trimmed WB, LB and BB vehicles. This method takes into account the stability of the vehicle for the selected mission trajectory.
3. *Propulsion:* Calculation of thrust available for an off-the-shelf rocket engine based on standard textbook method.
4. *Performance Matching:* Calculation of primary performance values for the deorbit and equilibrium glide flight path. Based on the equations derived in *Mission Analysis* step.
5. *Weights and Volume Budget:* Calculates overall weights and volume budgets of the primary hardware components based on parametric relationships.

The following describes each of the disciplinary analysis methods. The MATLAB analysis codes for all the disciplinary methods are provided in the Appendix B.

### Geometry Disciplinary Analysis

This section describes the development of geometry configurations as used in the LRV case-studies. The geometry analysis is the first discipline that defines the overall shape of the vehicle which is then used to calculate its aerodynamics and execute further disciplines. Several methods are used to define the geometry as per the characteristic of the vehicle. Kc̈hemann's tau defines the slenderness of the vehicle, and it is recognized as the primary geometric parameter that relates total volume with the planform area as follows: $\tau = V_{total} / S_{pln}^{1.5}$

This relationship is of significance as $\tau$ is used to scale the vehicle based on both volume and planform area. This scaling technique is significant as it relates the volume and area as compared to the usual

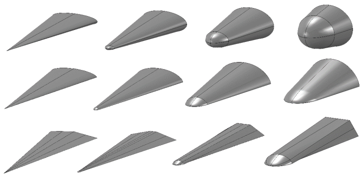


FIGURE 4.20 – Variation of Tau for three unique lifting body configurations shows the effects of volumetric scaling.

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[7] http://www.openvsp.org/

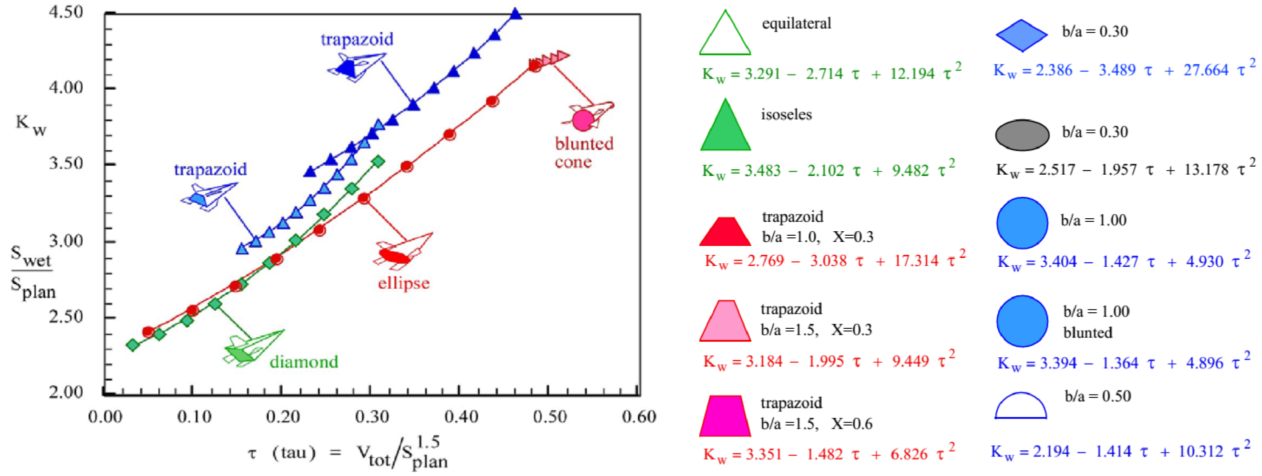


FIGURE 4.21 – Analytical geometric relationships are defined for several cross-section profiles by Czysz which are used here to define analytical geometry methods as function of Tau.

method of photographic scaling which scales only the area. In this manner $\tau$ represents a unique geometry profile. Czysz describes the importance of $\tau$ in the Hypersonic Convergence[52, 90] as follows:

> *"While working at the McDonnell Aircraft Company, the author (Czysz) was introduced to a unique approach to determining the geometric characteristics required by hypersonic configurations for different missions and propellants. Normally, to increase its volume, a vehicle is made uniformly larger (magnified), as in photographic scaling. That is, all dimensions are multiplied by a constant multiplier factor. This means that the configuration characteristics remain unchanged except that it is larger. The wetted area is increased by the square of the multiplier, while the volume is increased by the cube of the multiplier. In view of how the similitude parameter is defined, this scaling can have a very deleterious impact on the size and weight of the design when a solution is converged...This method used the cross-section geometry of highly swept bodies to increase the propellant volume without a significant increase in wetted area...This method (scaling by $\tau$) used the cross-section geometry of highly swept bodies to increase the propellant volume without a significant increase in wetted area."*

Czysz[52, 90] provides analytical relationships between various geometric parameters that are used to define a series of geometry profiles with varying base-area for lifting bodies. Figure 4.21 shows various vehicle cross section shapes defining the parametric relationships for geometry profiles. The parametric geometric relationships provided by Czysz are limited to the planform leading edge angle of 78 degrees which is a correct sweep angle for reentry gliders.

NASA open source geometry modeling software, OpenVSP is utilized as the primary geometry generation tool as it provides a flexible platform to build parametric geometries. The process of building a geometry configuration begins with selecting the desired configuration, a Lifting Body (LB) or Wing Body (WB). Then a cross section shape is

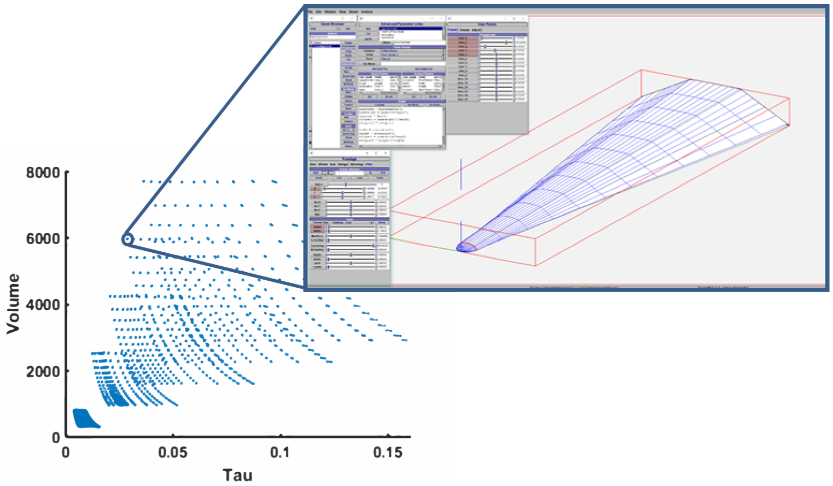


FIGURE 4.22 – Generation of geometric data with the OpenVSP analysis.

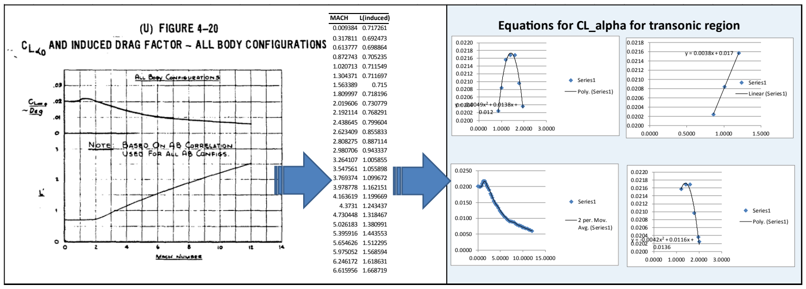
chosen and fixed model is generated.

Once the VSP file is prepared, an in-house analysis script utilize the calculation tools in VSP to generate a data table. The analysis script generates values of tau, volume, wetted area, frontal area etc. and makes a feasible geometry map. The geometry map also shows the sensitivity of the geometry to the changing geometric parameters. This allows the configuration behind the lookup table to be tuned for related disciplinary parameters. This process is highlighted below in Figure 4.22.

Note that each point in the above plot defines a unique outer mold shape for the given geometry profile. The last step in this process is filtering through the data and interpolating to a specific value of tau and planform for a single point. This is done through the formal geometry "method" script in the MATLAB. The method selected is essentially a table lookup function.

### Aerodynamic Method Analysis

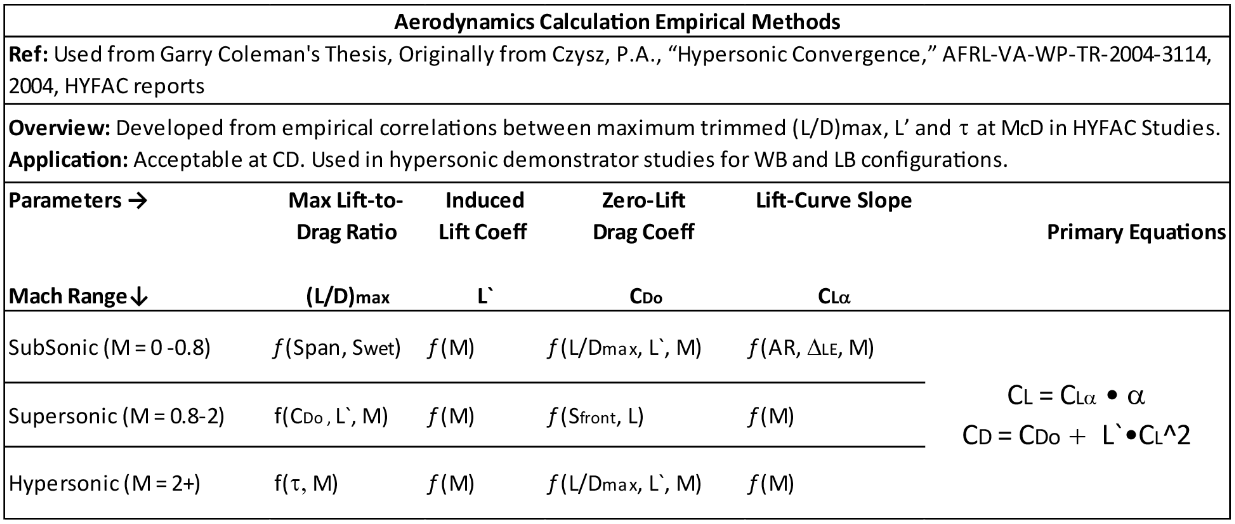
The aerodynamic discipline calculates the primary aerodynamic characteristics of the vehicle as function of the geometric parameters for the different flight regimes the vehicle is operating. The methods used here range from subsonic to hypersonic Mach number, and they are derived from empirical correlations for maximum trimmed L/D for a specific $\tau$ and induced drag coefficient (L'). The data for the method was generated initially at the McDonnel Douglas Company during the HyFAC studies[89] and the data are provided in the form of charts showing empirical relationships between various geometric parameters. This is a very expensive and accurate data set that was produced from extensive wind tunnel experimental tests on trimmed vehicle ge-



| MACH | L(induced) |
|---|---|
| 0.009384 | 0.717261 |
| 0.317811 | 0.692473 |
| 0.613777 | 0.698864 |
| 0.872743 | 0.705235 |
| 1.020713 | 0.711549 |
| 1.304371 | 0.711697 |
| 1.563389 | 0.715 |
| 1.809997 | 0.718196 |
| 2.019606 | 0.730779 |
| 2.192114 | 0.768291 |
| 2.438645 | 0.799604 |
| 2.623409 | 0.855833 |
| 2.808275 | 0.887114 |
| 2.980706 | 0.943337 |
| 3.264107 | 1.005855 |
| 3.547561 | 1.055898 |
| 3.769374 | 1.099672 |
| 3.978778 | 1.162151 |
| 4.163619 | 1.199669 |
| 4.3731 | 1.243437 |
| 4.730448 | 1.318467 |
| 5.026183 | 1.380991 |
| 5.395916 | 1.443553 |
| 5.654626 | 1.512295 |
| 5.975052 | 1.568594 |
| 6.246172 | 1.618631 |
| 6.615956 | 1.668719 |

FIGURE 4.23 – Creation of MATLAB lookup tables using aerodynamic data graphs for aerodynamic methods.

ometry shapes and has been proven reliable in multiple sizing executions by Chudoba[90], Coleman[27], Gonzalez[26] et al. The data is converted to lookup tables for application in the MATLAB analysis file. Figure 4.23 shows this process, while Table 4.1 shows the parametric relationships and primary aerodynamic equations among geometric and aerodynamic parameters.



**Aerodynamics Calculation Empirical Methods**

**Ref:** Used from Garry Coleman's Thesis, Originally from Czysz, P.A., "Hypersonic Convergence," AFRL-VA-WP-TR-2004-3114, 2004, HYFAC reports

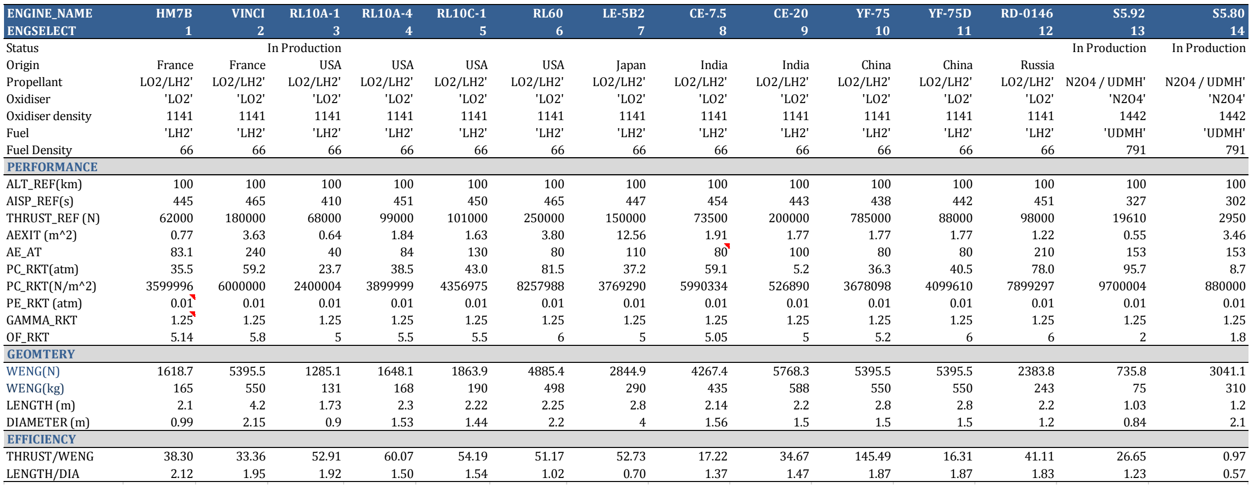
**Overview:** Developed from empirical correlations between maximum trimmed (L/D)max, L' and τ at McD in HYFAC Studies.
**Application:** Acceptable at CD. Used in hypersonic demonstrator studies for WB and LB configurations.

| **Parameters →** <br> **Mach Range ↓** | **Max Lift-to-Drag Ratio** <br> **(L/D)max** | **Induced Lift Coeff** <br> **L`** | **Zero-Lift Drag Coeff** <br> **$C_{Do}$** | **Lift-Curve Slope** <br> **$C_{L\alpha}$** | **Primary Equations** |
|---|---|---|---|---|---|
| SubSonic (M = 0 -0.8) | *f*(Span, $S_{wet}$) | *f*(M) | *f*(L/$D_{max}$, L`, M) | *f*(AR, $\Delta_{LE}$, M) | $C_L = C_{L\alpha} \bullet \alpha$ <br> $C_D = C_{Do} +$ L`•$C_L$^2 |
| Supersonic (M = 0.8-2) | f($C_{Do}$ , L`, M) | *f*(M) | *f*($S_{front}$, L) | *f*(M) | |
| Hypersonic (M = 2+) | f(τ, M) | *f*(M) | *f*(L/$D_{max}$, L`, M) | *f*(M) | |

TABLE 4.1 – Aerodynamic methods primary parametric relationships.

## Propulsion Method Analysis

A simple liquid rocket engine analysis is applied based on the standard textbook method by Sutton[91]. Rocket Performance analysis relations for the on and off design point determine the $I_{sp}$ and thrust available $T$. An engine deck of 14 existing upper-stage rocket engines has been created where physical characteristics of each rocket engine is stored. Then any of the engine can be selected by using a switch variable that enables the analysis method to calculate the frac-



| ENGINE_NAME | HM7B | VINCI | RL10A-1 | RL10A-4 | RL10C-1 | RL60 | LE-5B2 | CE-7.5 | CE-20 | YF-75 | YF-75D | RD-0146 | S5.92 | S5.80 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ENGSELECT | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
| Status | | | In Production | | | | | | | | | | In Production | In Production |
| Origin | France | France | USA | USA | USA | USA | Japan | India | India | China | China | Russia | | |
| Propellant | LO2/LH2' | LO2/LH2' | LO2/LH2' | LO2/LH2' | LO2/LH2' | LO2/LH2' | LO2/LH2' | LO2/LH2' | LO2/LH2' | LO2/LH2' | LO2/LH2' | LO2/LH2' | N2O4 / UDMH' | N2O4 / UDMH' |
| Oxidiser | 'LO2' | 'LO2' | 'LO2' | 'LO2' | 'LO2' | 'LO2' | 'LO2' | 'LO2' | 'LO2' | 'LO2' | 'LO2' | 'LO2' | 'N2O4' | 'N2O4' |
| Oxidiser density | 1141 | 1141 | 1141 | 1141 | 1141 | 1141 | 1141 | 1141 | 1141 | 1141 | 1141 | 1141 | 1442 | 1442 |
| Fuel | 'LH2' | 'LH2' | 'LH2' | 'LH2' | 'LH2' | 'LH2' | 'LH2' | 'LH2' | 'LH2' | 'LH2' | 'LH2' | 'LH2' | 'UDMH' | 'UDMH' |
| Fuel Density | 66 | 66 | 66 | 66 | 66 | 66 | 66 | 66 | 66 | 66 | 66 | 66 | 791 | 791 |
| **PERFORMANCE** | | | | | | | | | | | | | | |
| ALT_REF(km) | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| AISP_REF(s) | 445 | 465 | 410 | 451 | 450 | 465 | 447 | 454 | 443 | 438 | 442 | 451 | 327 | 302 |
| THRUST_REF (N) | 62000 | 180000 | 68000 | 99000 | 101000 | 250000 | 150000 | 73500 | 200000 | 785000 | 88000 | 98000 | 19610 | 2950 |
| AEXIT (m^2) | 0.77 | 3.63 | 0.64 | 1.84 | 1.63 | 3.80 | 12.56 | 1.91 | 1.77 | 1.77 | 1.77 | 1.22 | 0.55 | 3.46 |
| AE_AT | 83.1 | 240 | 40 | 84 | 130 | 80 | 110 | 80 | 100 | 80 | 80 | 210 | 153 | 153 |
| PC_RKT(atm) | 35.5 | 59.2 | 23.7 | 38.5 | 43.0 | 81.5 | 37.2 | 59.1 | 5.2 | 36.3 | 40.5 | 78.0 | 95.7 | 8.7 |
| PC_RKT(N/m^2) | 3599996 | 6000000 | 2400004 | 3899999 | 4356975 | 8257988 | 3769290 | 5990334 | 526890 | 3678098 | 4099610 | 7899297 | 9700004 | 880000 |
| PE_RKT (atm) | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| GAMMA_RKT | 1.25 | 1.25 | 1.25 | 1.25 | 1.25 | 1.25 | 1.25 | 1.25 | 1.25 | 1.25 | 1.25 | 1.25 | 1.25 | 1.25 |
| OF_RKT | 5.14 | 5.8 | 5 | 5.5 | 5.5 | 6 | 5 | 5.05 | 5 | 5.2 | 6 | 6 | 2 | 1.8 |
| **GEOMTERY** | | | | | | | | | | | | | | |
| WENG(N) | 1618.7 | 5395.5 | 1285.1 | 1648.1 | 1863.9 | 4885.4 | 2844.9 | 4267.4 | 5768.3 | 5395.5 | 5395.5 | 2383.8 | 735.8 | 3041.1 |
| WENG(kg) | 165 | 550 | 131 | 168 | 190 | 498 | 290 | 435 | 588 | 550 | 550 | 243 | 75 | 310 |
| LENGTH (m) | 2.1 | 4.2 | 1.73 | 2.3 | 2.22 | 2.25 | 2.8 | 2.14 | 2.2 | 2.8 | 2.8 | 2.2 | 1.03 | 1.2 |
| DIAMETER (m) | 0.99 | 2.15 | 0.9 | 1.53 | 1.44 | 2.2 | 4 | 1.56 | 1.5 | 1.5 | 1.5 | 1.2 | 0.84 | 2.1 |
| **EFFICIENCY** | | | | | | | | | | | | | | |
| THRUST/WENG | 38.30 | 33.36 | 52.91 | 60.07 | 54.19 | 51.17 | 52.73 | 17.22 | 34.67 | 145.49 | 16.31 | 41.11 | 26.65 | 0.97 |
| LENGTH/DIA | 2.12 | 1.95 | 1.92 | 1.50 | 1.54 | 1.02 | 0.70 | 1.37 | 1.47 | 1.87 | 1.87 | 1.83 | 1.23 | 0.57 |

TABLE 4.2 –
Deck of liquid rocket engines created to be used as a quick switch method with standard textbook propulsion analysis.

tion thrust (as specified by the user) that is provided by the selected engine. With this implementation, the need to size the engine (rubber engine) is eliminated and existing off-the-shelf technology engines can be quickly selected. The engine dry weight and volume are also used in the weights and volume estimation method which allows the sizing code to accommodate for the size and weight of the engine inside vehicle's geometry mold. Table 4.2 shows the upper-stage engines used for this analysis.

### Performance Matching

Performance matching is fundamentally based on the primary performance relations described in the prio *Mission Analysis* step. The only difference here is that it is primarily used with vehicle subsystem parameters that are calculated in the geometry, aerodynamics and propulsion disciplines. The performance matching step therefore provides a measure of the main performance attributes required by the vehicle to match the mission objectives. In this manner, it is used as a check on the overall sizing code to calculate the total amount of fuel required to perform the mission.

### Weights and Volume Budget

This is the last discipline which calculates the total weight and volume for the vehicle based on the above outputs stemming from all other disciplines. The method used here is a modified version of the parametric relations given by VDK and Czysz[92] for the second stage of a TSTO vehicle. The method calculates the vehicle's weight and volume budgets using a set of coefficients that account for the technology level by the use of empirical coefficients that account for the thermal protection system in the total structure of the vehicle and other fixed systems to calculate the empty weight of the vehicle. An additional volume estimate is used to account for the volumes of subsystem, which is used to calculate a second estimate of vehicle's empty weight. Through these two independent calculations of the total empty weight of the system, the weight and volume method provides a way to implement a unique convergence criteria on the system which is explained in next section. The primary equations and coefficient's values are shown in the Figure 4.24 taken from [92].

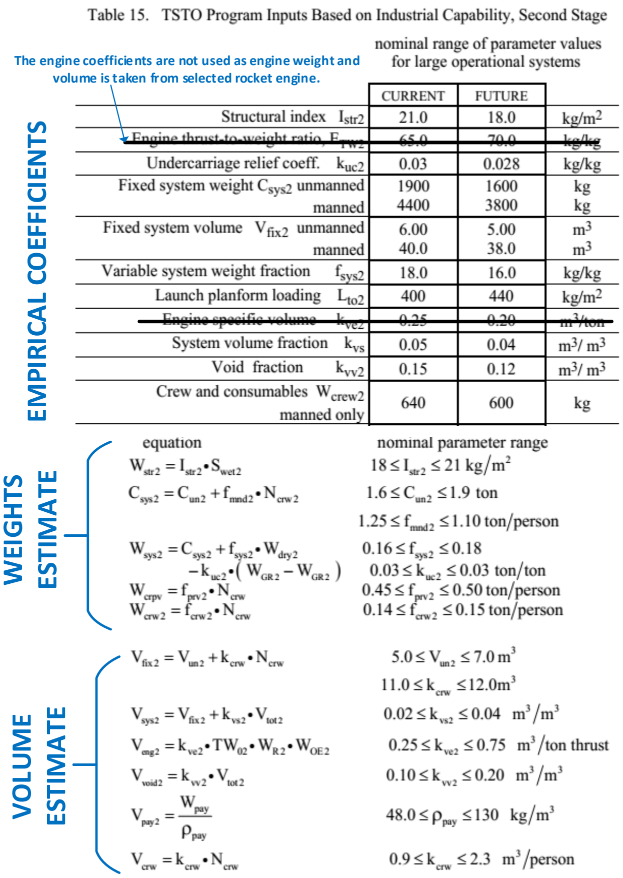


Table 15. TSTO Program Inputs Based on Industrial Capability, Second Stage

The engine coefficients are not used as engine weight and volume is taken from selected rocket engine.

EMPIRICAL COEFFICIENTS

| | nominal range of parameter values for large operational systems<br>CURRENT | FUTURE | |
|---|---|---|---|
| Structural index $I_{str2}$ | 21.0 | 18.0 | kg/m$^2$ |
| ~~Engine thrust-to-weight ratio, $F_{TW2}$~~ | ~~65.0~~ | ~~70.0~~ | ~~kg/kg~~ |
| Undercarriage relief coeff. $k_{uc2}$ | 0.03 | 0.028 | kg/kg |
| Fixed system weight $C_{sys2}$ unmanned<br>manned | 1900<br>4400 | 1600<br>3800 | kg<br>kg |
| Fixed system volume $V_{fix2}$ unmanned<br>manned | 6.00<br>40.0 | 5.00<br>38.0 | m$^3$<br>m$^3$ |
| Variable system weight fraction $f_{sys2}$ | 18.0 | 16.0 | kg/kg |
| Launch planform loading $L_{to2}$ | 400 | 440 | kg/m$^2$ |
| ~~Engine specific volume $k_{ve2}$~~ | ~~0.25~~ | ~~0.20~~ | ~~m$^3$/ton~~ |
| System volume fraction $k_{vs}$ | 0.05 | 0.04 | m$^3$/ m$^3$ |
| Void fraction $k_{vv2}$ | 0.15 | 0.12 | m$^3$/ m$^3$ |
| Crew and consumables $W_{crew2}$ manned only | 640 | 600 | kg |

WEIGHTS ESTIMATE

| equation | nominal parameter range |
|---|---|
| $W_{str2} = I_{str2} \bullet S_{wet2}$ | $18 \le I_{str2} \le 21 \text{ kg/m}^2$ |
| $C_{sys2} = C_{un2} + f_{mnd2} \bullet N_{crw2}$ | $1.6 \le C_{un2} \le 1.9 \text{ ton}$ |
| | $1.25 \le f_{mnd2} \le 1.10 \text{ ton/person}$ |
| $W_{sys2} = C_{sys2} + f_{sys2} \bullet W_{dry2}$ | $0.16 \le f_{sys2} \le 0.18$ |
| $- k_{uc2} \bullet ( W_{GR2} - W_{GR2} )$ | $0.03 \le k_{uc2} \le 0.03 \text{ ton/ton}$ |
| $W_{crpv} = f_{prv2} \bullet N_{crw}$ | $0.45 \le f_{prv2} \le 0.50 \text{ ton/person}$ |
| $W_{crw2} = f_{crw2} \bullet N_{crw}$ | $0.14 \le f_{crw2} \le 0.15 \text{ ton/person}$ |

VOLUME ESTIMATE

| equation | nominal parameter range |
|---|---|
| $V_{fix2} = V_{un2} + k_{crw} \bullet N_{crw}$ | $5.0 \le V_{un2} \le 7.0 \text{ m}^3$ |
| | $11.0 \le k_{crw} \le 12.0 \text{m}^3$ |
| $V_{sys2} = V_{fix2} + k_{vs2} \bullet V_{tot2}$ | $0.02 \le k_{vs2} \le 0.04 \text{ m}^3/\text{m}^3$ |
| $V_{eng2} = k_{ve2} \bullet TW_{02} \bullet W_{R2} \bullet W_{OE2}$ | $0.25 \le k_{ve2} \le 0.75 \text{ m}^3/\text{ton thrust}$ |
| $V_{void2} = k_{vv2} \bullet V_{tot2}$ | $0.10 \le k_{vv2} \le 0.20 \text{ m}^3/\text{m}^3$ |
| $V_{pay2} = \dfrac{W_{pay}}{\rho_{pay}}$ | $48.0 \le \rho_{pay} \le 130 \text{ kg/m}^3$ |
| $V_{crw} = k_{crw} \bullet N_{crw}$ | $0.9 \le k_{crw} \le 2.3 \text{ m}^3/\text{person}$ |

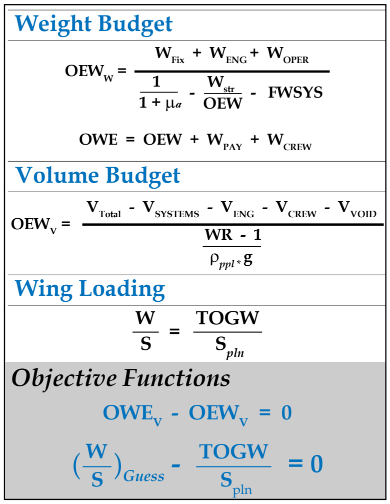
FIGURE 4.24 – Primary Weight and Volume budget equations as given by VDK and Czysz. The engine parameters and equations are not used here and taken from Table 4.2 for selected rocket engines.

The individual disciplines calculated here are combined next in a specified manner to create a synthesis sizing code.

### 4.3.3 *Hardware Selection*

This section provides details how to generate the multi-disciplinary analysis (MDA) process logic which combines the disciplinary methods analysis explained in the previous section. The MDA is applied to size the vehicle to identify first physical characteristics estimates of key variables such as weight, volume, and physical dimensions. Such information is vital to any feasibility investigation.

The sizing logic and related disciplines arrangement is shown using the Nassi-Shneiderman diagram in Figure 4.26. The sizing methodology used for this study is based on a constant mission sizing logic. The logic and general approach used is the constant mission sizing logic of Hypersonic Convergence by Czysz[52]. It is a first order sizing application where the most critical design parameters are recognized and employed to find a design solution space of converged design points. It represents a multi-disciplinary analysis tool-set where key technology parameters are recognized. These parameters are used to characterize the whole vehicle system, allowing technology fore- casting studies, mission exploration studies, design feasibility studies and more. This sizing-based forecasting approach is used to measure the design with current day available industry capability versus future technology. In the process the system identifies if there is any specific requirement which can cause the program to fail in later stages (show stopper assessment). The complete MDA developed in the present context is a modular structure implementation, composed of individual disciplinary analysis methods and the integration process.



$$OEW_W = \frac{W_{Fix} + W_{ENG} + W_{OPER}}{\frac{1}{1+\mu_a} - \frac{W_{str}}{OEW} - FWSYS}$$

$$OWE = OEW + W_{PAY} + W_{CREW}$$

$$OEW_V = \frac{V_{Total} - V_{SYSTEMS} - V_{ENG} - V_{CREW} - V_{VOID}}{\frac{WR - 1}{\rho_{ppl} * g}}$$

$$\frac{W}{S} = \frac{TOGW}{S_{pln}}$$

$$OWE_V - OEW_V = 0$$

$$\left(\frac{W}{S}\right)_{Guess} - \frac{TOGW}{S_{pln}} = 0$$

FIGURE 4.25 – The essential objective function must be satisfied for executing the fundamental convergence logic.

The sizing logic is implemented through the *Analysis Process* component of the DBMS where the fundamental independent and dependent systems variables are defined. The independent variables (planform area and wing-loading) are the initial input to the system which are fed into the geometry methods to start the sizing analysis. The disciplines are then executed for a fixed value of vehicle slenderness parameter $\tau$ in the following orderly sequence; geometry, aerodynamics, propulsion, performance and weights and volume. The dependent variables (TOGW and weights estimate from weight and volume method) are calculated at the end which are then used with the independent variables to satisfy the objective function. Through this iterative process when the objective function is satisfied, a converged vehicle is obtained for which the primary disciplinary results have been calculated.

The vehicle's planform area and wing-loading are the primary independent variables that are iterated until a converged design solution is achieved. The designer provides an initial guess estimate of these variables which feeds into the MDA framework. The geometry module acts as the 'gearbox' of the synthesis system where the vehicle's geometry could be scaled using just $\tau$ which accounts for weight and volume effects collectively . For a fixed $\tau$, the geometry module passes vehicle's geometric characteristics to the aerodynamic analysis method which calculates lift and drag values for the vehicle for a specified

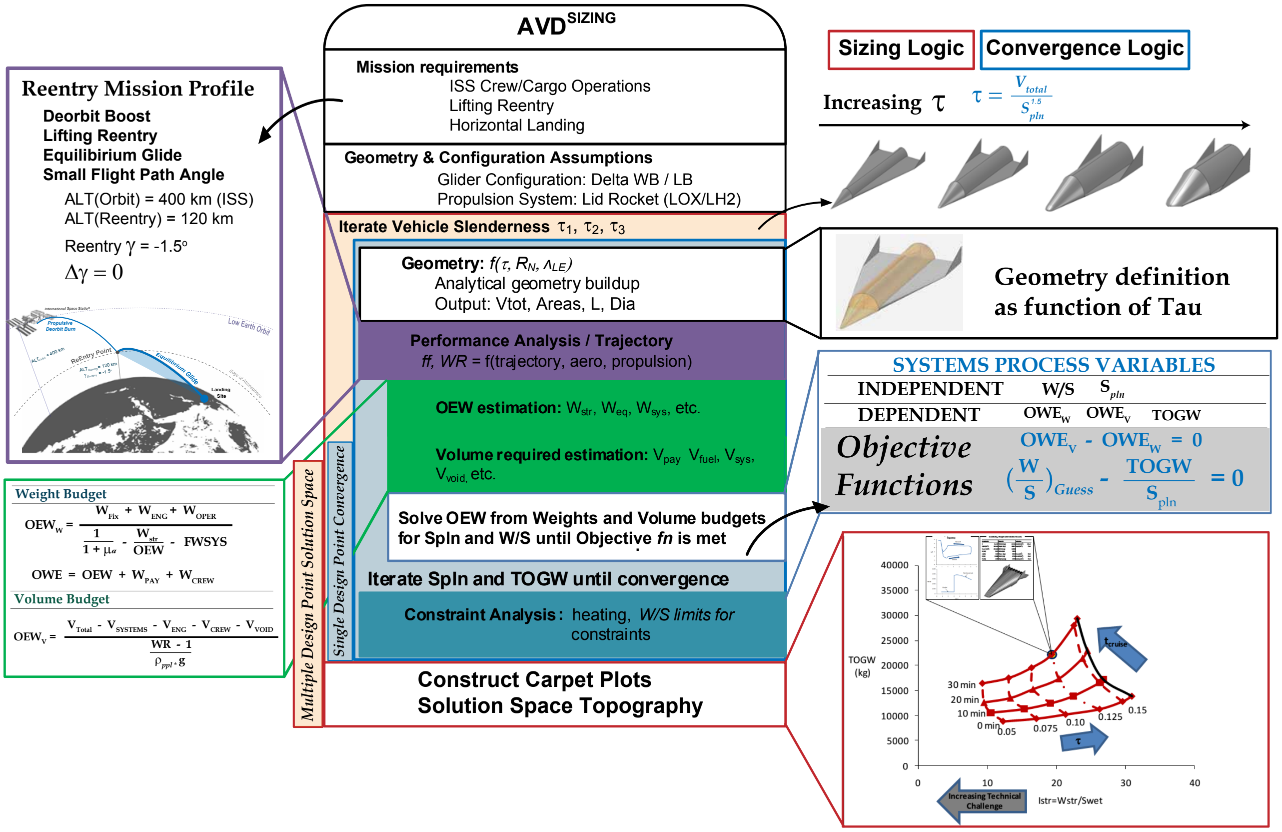


FIGURE 4.26 – Fundamental logic of the sizing methodology implemented into a software called AVD$^{SIZING}$.

mission profile. The aerodynamic results are passed to the propulsion module next which calculates the required thrust for a selected propulsion type. The performance calculation method is then applied to find the fuel fraction and vehicle's mass ratio for the overall mission trajectory. The results from the geometry, aerodynamics, propulsion, and performance matching modules are used to assess the vehicle's weight and volume. For a given vehicle slenderness parameter ($\tau$), the planform area and wing loading are iterated through the total design process until weight and volume available equal weight and volume required. The algebraic sizing process solves for weight and planform area simultaneously through converging weight and volume for a given set of design variables.

As the system is sized for one $\tau$ by iterating the independent variables, an outer sweep of $\tau$ thus provides a means to develop a solution space of converged vehicles which are sized to the same mission. The sizing code is created by the DBMS as a modular structure of the MATLAB script files for disciplinary analysis and a central input file to specify the required disciplinary and mission variables input values. These variables are iterated with $\tau$ in the outer sweep to size multiple vehicle concepts and develop design solution continuum. The process is further made clear in the execution case-studies in Section 4.4. The LRV case-studies are sized using this generic sizing methodology where the geometry or the aerodynamic method is adjusted according to the shape of the configuration.

The final outcome for this step is the sizing of a converged vehicle concept and subsequent creation of a solution space which provides a continuum of the vehicle design solution space topography. These vehicles are all sized to meet the initial mission objectives specified, and hence they establish the physical and technical feasibility at this point. The next step then develops an estimate of the total cost for each vehicle in the solution space and calculates an overall performance efficiency index. With these two estimates, the solution space is revisited and each vehicle concept is now measured for a cost-per-performance measure.

### *4.3.4 Cost/Performance*

With the sizing results and solution space definition available, this last step of the solution process estimates the life-cycle cost for the LRV concept continuum and it normalizes with the overall performance efficiency factor to scan the technically feasible solution space for the most cost beneficial design solutions. For this purpose, the current section addresses two parts. The first part is the estimation of total cost, while the second part is the formulation of the overall performance measurement factor.

#### TOTAL COST ESTIMATE

The cost estimation model used here is based on D. E. Koelle's *Handbook of Cost Engineering and Design of Space Transportation Systems with TransCost 8.2 Model Description*[93]. Transcost model is a widely accepted cost estimation model which calculates overall life-cycle cost of space access systems by breaking down the total life-cycle cost into several smaller segments. Each segment estimates the cost associated with a life-cycle phase starting from development phase to all the way into operations. Each cost estimate (referred to as submodels by Koelle) is derived based on empirical Cost Estimating Relationships (CER) which are quite simple equations providing cost estimates of a system or an element based on the respective mass. The cost submodels used here address three major life-cycle phases, namely; 1) Development Cost (not calculated for the existing off-the-shelf engines), 2) Production cost (calculated for engines and LRV vehicle), and 3) Direct Operations Cost (includes Ground Operations and Flight Operations). The estimated costs are in the unit 'work-years' ($WYr$) which is defined as "the total company annual budget divided by the number of productive full-time people [93]." Since the primary use of this step is to have the cost estimates for the purpose of estimating the overall value of a product[8], the $WYr$ unit is used here and will not be converted to the dollar amount (Koelle provides a conversion factor for this purpose which is neglected in this research). A total of 12 different cost factors, $f_0 - f_{11}$ are used in the Transcost model which are used to derive the CERs to estimate the required costs for elements (engines, propulsion module etc) and the systems (vehicles, stages etc). The cost factors used in this section are listed below:

- $f_0$ – project systems engineering and integration factor;
- $f_1$ – technical development standard correlation factor;
- $f_2$ – technical quality correlation factor;
- $f_3$ – team experience factor;
- $f_4$ – cost reduction factor from Learning factor;
- $f_6$ – cost growth factor;
- $f_7$ – parallel organization factor;
- $f_8$ – country productivity factor;
- $f_{10}$ – techn. progress cost reduction factor;
- $f_{11}$ – commercial cost reduction factor.

These factors form the CERs for the LRV are discussed next.

Values of cost factors used for LRVs:
» $f_0 = 1.04$
» $f_1 = 1.1$
» $f_2 = 1$
» $f_3 = 1.3$
» $f_4 = 0.58$
» $f_6 = 1.3$
» $f_7 = 1.2$
» $f_8 = 1$
» $f_9 = 1.08$
» $f_{10} = 0.8$
» $f_{11} = 0.5$

### » TOTAL LIFE-CYCLE COST MODEL

The total cost of the LRV vehicle is composed of three main submodels, namely; 1) Development Cost, 2) Production Cost, and 3) Operations Cost;

$$\text{Cost}_{Tot} = \text{Dev.Cost}_{Tot} + \text{Prod.Cost}_{Tot} + \text{Ops.Cost}_{Tot} \tag{4.20}$$

Following then are the CERs for each submodel;

» *Development costs* The total development cost for the LRV is calculated of only the LRV stage and does not include the cost of on-board rocket engines. It is given by the following equation:

$$\text{Total development cost} = f_0\, H_{VW}\, f_6\, f_7\, f_8 \tag{4.21}$$

where

$$H_{VW} = 1.420\, M^{0.35}\, f_1\, f_2\, f_3\, f_{10}\, f_{11} \tag{4.22}$$

[8] It must be noted that this last step measures the cost-per-performance for the entire solution space and thus provides an estimate of the overall value for the vehicles. The goal here is to predict the life-cycle cost, but instead to find which design concept provides the most performance for the minimum cost and not the one that costs the minimum. This is referred to here as the value impact of each vehicle over the entire solution space

» *Production costs* The total production cost of the LRV is calculated for the on-board liquid rocket engines and the LRV stage vehicle. It is given by the following equation:

$$\text{Total Production cost} = f_0\,(F_{ET} + F_{VW})\,f_9 \tag{4.23}$$

where, Liquid Rocket Production Cost $F_{ET}$, and the LRV Stage Production Cost $F_{VW}$, are calculated as follows;

$$F_{ET} = 2.29\,M^{0.545}\,f_4\,f_8\,f_9\,f_{10}\,f_{11} \tag{4.24}$$

$$F_{VW} = 5.83\,M^{0.606}\,f_4\,f_8\,f_{10}\,f_{11} \tag{4.25}$$

» *Operations Cost* Koelle defines Direct Operations Cost as composed of following elements,

- Ground Operations
- Materials & Propellants
- Flight Operations
- Transport & Recovery
- Fees & Insurance

Of these elements, only the Ground Cost and the Flight Operations cost are included to calculate the Operations Cost for the LRVs. The following set of CERs are given by Koelle for these elements;

$$\text{DOC} = C_{OPS} + C_M \tag{4.26}$$

where, the Ground Operations cost, $C_{OPS}$ and the Flight Operations Cost, $C_M$ are given by the following set of equations;

$$C_{OPS} = 12.24\,{M_0}^{0.67}\,L^{-0.9}\,f_4\,f_8\,f_{11} \tag{4.27}$$

$$C_M = 60\,L^{-0.65}\,f_4\,f_8 \tag{4.28}$$

$M_0$ is the TOGW at the takeoff and L is the launch rate, L = 25 flights per year assumed flight rate here.

Once the total cost is calculated, the next and final step is to calculate the overall performance of the LRV concept. For this purpose, a performance efficiency index is calculated which provides a holistic measure of the overall performance of the LRV vehicles. With this parameter, the total vehicle cost is normalized with the performance efficiency factor to define a value index for the vehicle. The performance efficiency factor and other performance indicating parameters are defined next.

### Primary Performance Measuring Indices

Having completed the total cost calculation, the next step is to define critical performance measuring indices that holistically define the LRV's overall efficiency and benefits. This is done to enable a consistent comparison among LRV vehicles of varying shape, size and disciplinary trades. The following three holistic index parameters are defined which are composed of vehicle's primary physical parameters and thus represents a much broader range of desired physical characteristics and performance capabilities of the vehicle than the constituting parameters[9]:

1. *Performance Efficiency Index:* This index was first introduced by Eggers et al. in 1956 in a landmark study[20] that provided one of the first comparative analysis standards for the hypervelocity vehicles. Eggers defines an overall performance measuring factor following the logic of the classical Breguet Range Equation for aircraft. The performance index is composed of gross performance parameters as shown in the following equation:

$$Perf_{Eff} = (L/D) * V_{entry}/V_{satellite} * g * I_{sp}/V_{satellite} \tag{4.29}$$

2. *Volumetric Efficiency Index:* This index defines the overall volumetric efficiency of the geometry and indicates its efficiency to store the maximum volume in minimum surface area.

$$Vol_{Eff} = V_{Total}^{2/3}/S_{Wetted} \tag{4.30}$$

3. *Structural Efficiency Index:* Czysz, Bruno and Chudoba[52, 90] define a structural efficiency term, $I_{STR}$. This variable correlates the total structural weight of the vehicle to the wetted surface area. This factor is representative of the manufacturing capability of the industry.[10]

$$I_{Str} = W_{Str}/S_{Wetted} \tag{4.31}$$

## 4.3.5 *Software Implementation*

The *Physical Solution Architecture* of four steps of the SAS-GDSP solution is described at this point. As mentioned earlier, the execution of step-2, *'Technology Requirement'* and step-3, *'Hardware Selection'* is implemented with the DBMS while the rest of the solution is implemented independent and outside of the DBMS. Figure 4.27 shows the overall software execution of the complete SAS-GDSP solution.

It must be mentioned again that the SAS-GDSP is proposed as a step-wise executable process and not a standalone system. Therefore, the execution of the complete process implements various software

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[9] Just like the Kücherman's slenderness parameter $\tau$ is a better indicator of the geometry as it involves volume and planform area, two significant geometric characteristics, than a simple length/diameter parameter that is also used to define the slenderness of the geometry. Similarly, these performance measuring indices are composed of major vehicle parameters like L/D, $I_{sp}$ etc. and include more information about the vehicle's overall efficiency and performance.

[10] Czysz provides $I_{Str}$ limits estimate for the current and future industry capability, circa 1980 which is used as a constraint factor for the solution space.

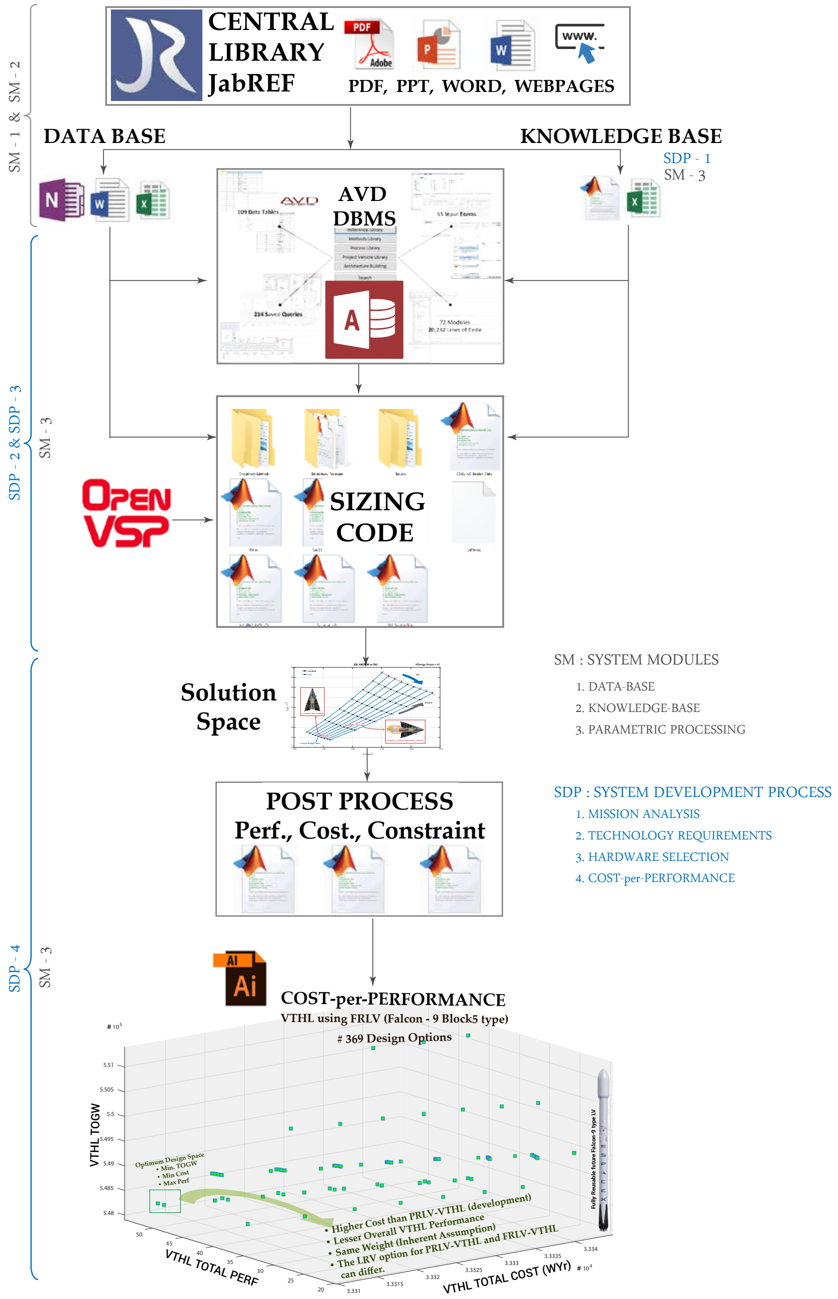


FIGURE 4.27 – SAS-GDSP software suite shows execution of four SDPs comprised of 3 SMs.

systems. Clearly, the SAS-GDSP solution represent a cross-platform software integration implementation. For the present study, following software capabilities were employed:

- JaBREF (stores PDFs, PPTs, Webpages, Word)

- MS Office Suite (Word, Excel, Access, OneNote)
- MATLAB (for processing)
- OpenVSP (for modeling geometry)
- Adobe Illustrator (for image processing)

Figure 4.27 shows the stepwise execution of the *Logical Solution Architecture* of the SAS-GDSP explained in the Chapter 3 and is a representative of the overall Logical Solution Architecture concept visualized in Figure 4.1. Next section describes the execution of the SAS-GDSP solution for the proposed LRV case-studies.

## 4.4 *SAS-GDSP Application Results*

This section describes the implementation of the *Physical Solution Architecture* of the GDSP solution as described above. Three distinct case-studies are executed here for the generic ISS resupply mission which is described in the section 4.3.1, see Figure 4.19.

The first case-study is the sizing of a legacy LRV program, the X-20 Dyna-Soar. This case-study is executed with the aim to perform a verification and validation of the results obtained from the GDSP solution process by comparing against the legacy data. The X-20 is primarily a case-study for technical verification and validation of the methods selected and not to explore the performance-to-cost solution space for a new design. Thus, this case-study follows only the first three steps of the generic GDSP solution process and the cost-per-performance implementation is not executed here.

The second case-study then implements the GDSP solution for a generic Lifting-Body (LB) configuration where the complete GDSP solution is executed to explore the design continuum solution space for the generic LB configuration. An analogous case-study is also implemented for a generic Wing-Body (WB) configuration in the third case-study. Both of these The generic case-study is executed for the same mission objective of LEO reentry from ISS altitude for a 1 person crew and 450 kg of payload requirements. The common mission objective then provides a base-line for consistent comparison among generic configurations for varying shape, size and technology implementation.

### 4.4.1 *Verification Case: The Boeing X-20 Dyna-Soar*

This case-study focuses on a legacy program from the days of the space race between the USA and the USSR. The era of competition to conquer space saw leaps and bounds in space related technology in the span of only a few years. In the years following the space race, the industry saw a halt in the rapid progress. The X-20 Dyna-Soar was the first industrial scale program initiated in 1957 to develop the first LRV as a routine access to orbit capability. The program saw many highs, acquiring new knowledge of the hypersonic regime, and it was the largest program in the country. Then with the inception of the Gemini program as the precursor to the Apollo, the direction of the government turned towards the easy to understand, but low on performance, ballistic capsule designs. The X-20 was canceled in late 1963, citing reasons that the program lacked a clear direction and mission definition. It would not be until 20 years that the Space Shuttle would execute the same mission objectives and be the first LRV program.

Since the X-20 shows a data and knowledge rich history, this case-study acts as the perfect example for the verification of the sizing results obtained by the application of the SAS-GDSP solution. With this first case-study the focus is primarily on the validation of the methods and process used for sizing a well-known legacy LRV study. Thus, with this case, only the first three steps are applied to demonstrate the capability of the solution process to develop a technology feasibility solution space. The last step of measuring the cost-per-performance solution space is not applied to this study as the X-20 was primarily an exploration case which was pushing the boundary of the hypersonic knowledge available at the time. The logic of applying the cost-per-performance step is to explore the business-case solution space for a project. Thus, this last step will be applied for generic case-studies exploring the design solution space for the lifting and wing body configurations.

**Case-Study Description** The X-20 Dyna-Soar was the first operational-vehicle initiative to apply all of the then available high-speed knowledge onto a single program with practical applications. Since the early

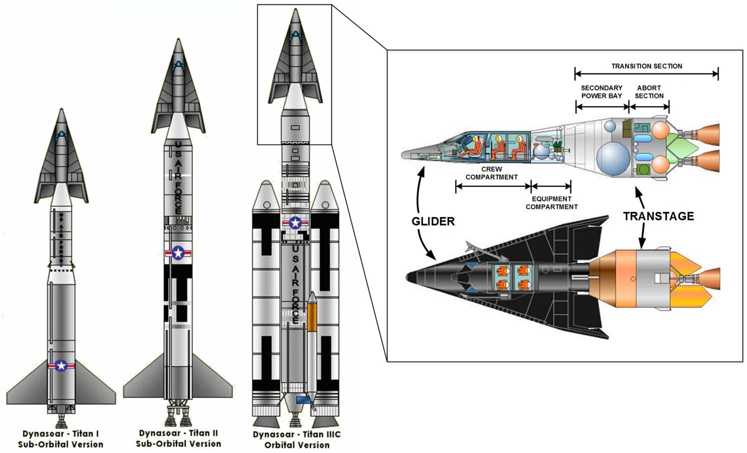


FIGURE 4.28 – Dyna-Soar Program phases and Vehicle Layout

1950s, the USAF had been involved in hypersonic glider research activities under separate projects like BOMI, HYWARDS, and ROBO [31, 75]. In 1957, the USAF defined the X-20 program, combining the previous studies of BOMI, ROBO and HYWARDS under one umbrella. Boeing was awarded the contract to develop the X-20 glider while The Martin Company was selected to develop the expendable booster. The program was to be developed in multiple stages; each stage's mission requirements becoming sequentially more demanding. Phase one of the program was aimed to deliver a conceptual test vehicle as a test bed for the boost-glide operation. This stage of the program was supposed to be a proof-of-concept, validating the feasibility of the technology and hardware. The second stage of the program would deliver a sub-orbital mission capable vehicle with limited capabilities over a restricted range of around 5000 nmi. This stage was a single-person vehicle. The third and final stage of the program aimed at developing the first-of-it-kind hypersonic, global range, strategic bomber/reconnaissance system. This variant would attain orbital speeds and performs single and multi-orbit missions. The vehicle at this stage had multiple versions with multi-person crews and mission profiles to execute a variety of operations that included servicing satellites in orbit, crew transportation, and re-supply missions. The main objective of the Dyna-Soar program was to obtain hypersonic flight data and experience to develop a space bomber with global range.

The name "Dyna-Soar" stands for Dynamic-Soaring. Dynamic-soaring is a flying technique most commonly used by birds and hang-gliders to save energy while covering maximum range. The X-20 was designed to use this method to gain energy by crossing between air masses of different velocity due to changing atmospheric density layers. The X-20 was supposed to be the first space-plane in an era that was later dominated by capsule designs operated under the Mercury, Gemini, and Apollo programs.

The X-20 was a VTHL system configuration. The Titan II and Titan IIIc boosters would provide the launch and orbital access capability in subsequent phases of the program. The glider was a horizontal landing low delta-wing design, as shown in Figure 4.28. The stability and control during re-entry was provided by the winglets and elevons; there was no conventional vertical tail. A new super alloy—Rene 41—was used for the framework of the vehicle. Molybdenum sheets covered the bottom surface as TPS. A general layout of the vehicle had the pilot compartment, followed by equipment bay used to house the payload (scientific and reconnaissance equipment, weapons etc.). The orbital variant had an extended pilot compartment allowing for a four-person-mid-deck. The vehicle retained the upper-most rocket stage from the launcher (Titan IIIC) for in-orbit maneuvers and de-orbital burns for reentry. This propulsion module, called a transtage, was jettisoned prior to decent into the atmosphere[31].

### Sizing Logic and Disciplinary Methods Overview

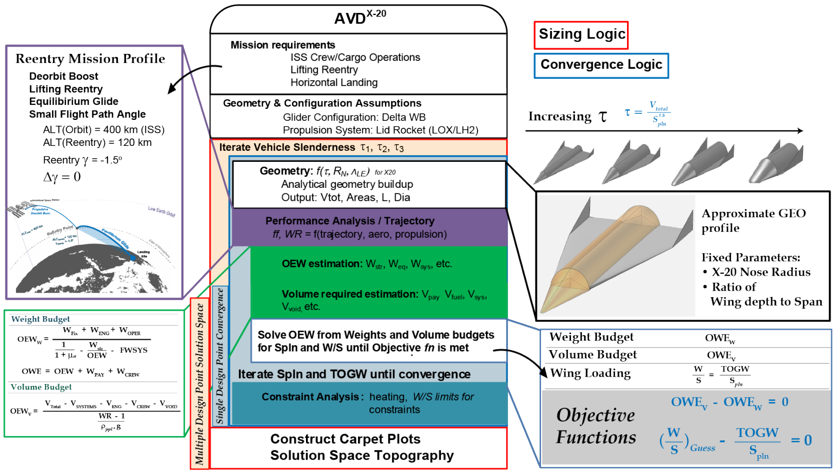


FIGURE 4.29 – Multidisciplinary analysis approach applied for sizing X-20 case-study

The sizing methodology is shown in Figure 4.29, where the program logic and disciplinary breakdown is represented in the order of execution. A first-order geometry estimate is the beginning point of the procedure where the geometry method is an analytical method defined by simplifying the vehicle configuration into elementary geometry components. The overall geometric properties are calculated as a function of the vehicle slenderness parameter $\tau$ ($\tau = V_{total}/S_{pln}^{1.5}$). The geometry feeds into discipline specific modules in the following order of execution: aerodynamics, propulsion, performance analysis, and finally weight and volume estimates. Weight and volume balancing acts as the heart of the process. The planform and wing-loading are iterated for a given $\tau$ until the weight and volume available equal the weight and volume required. The disciplinary methods used are summarized in Table 4.3.

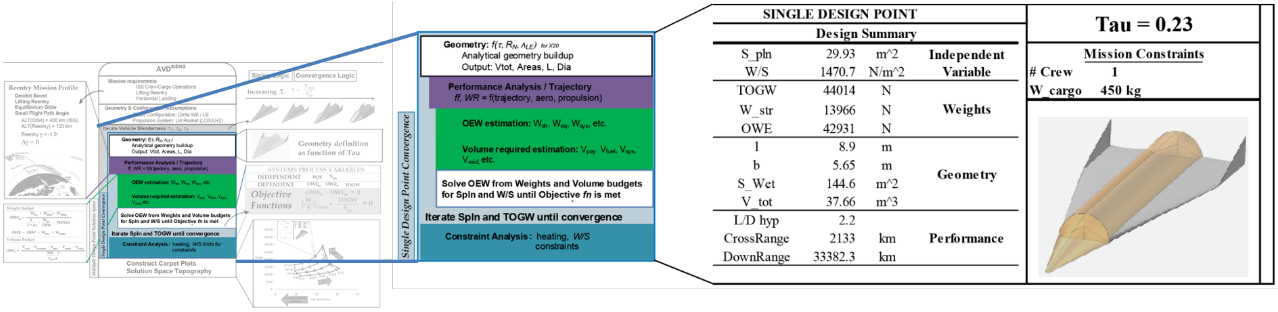
### Single point convergence

A single-point convergence design study is executed. The single-point was for a fixed value of $\tau = 0.23$; a value of 0.23 was calculated as a rough approximation from the original X-20 three-view drawings. The convergence logic iterates planform area and wing loading until the objective function is satisfied. The result is a converged vehicle solution, the results for which are shown in the Figure 4.30. The vehicles defining variables are shown here, identifying the overall vehicle configuration characteristics and performance. Between all the disciplines, the sizing process calculates 27 primary outputs. Each one is a variable

| Discipline | Application | Description | Reference |
|---|---|---|---|
| Geometry | | | |
| | General Configuration | Configuration buildup by means of elementary elements: semisphere, half-cylinder, truncated cone, etc. | |
| Aerodynamics | | | |
| | Subsonic, Supersonic, and Hypersonic | Empirical McDonald Douglas aerodynamic relations for estimating lift-to-drag ratio $(L/D)_{max}$, lift curve slope $C_{L_\alpha}$, induced drag factor $L'$, and zero lift-drag coefficient $C_{D_o}$ | HyFac[94],<br>Coleman[27] |
| Propulsion | | | |
| | Rocket Performance | Off and on design point analytical relations for determination of $I_{sp}$ and thrust available $T$ | Sutton[91] |
| Performance Matching | | | |
| | De-Orbit | Analytical relation for the de-orbit problem identifying $\Delta V$ and entry velocity, $V_e$, as a function of entry flight path angle, $\gamma_e$ and de-orbit parking orbit $r_p$ | Low[85] |
| | Cross-Range | Analytical relation for cross-range determination as a function of a constant optimum bank angle $\phi_{opt}$ and $L/D$ | Vinh[86] |
| | Down-Range | Analytical relation for determination of max down-range as a function of $L/D$ and atmospheric starting glide velocity | Galman[88] |
| | Glide | Relations for small flight path angle glide from re-entry to landing | Miele[87] |
| Aerothermodynamics | | | |
| | Max Heat Flux | Max heat flux correlation as a function of glide weight $W$, coefficient of lift $C_L$, planform area $S_{pln}$, and nose radius $r_N$ | Galman[88] |
| Weight and Volume | | | |
| | Weight | Empirical relations for the identifying of weight contributions | Czysz[52] |
| | Volume | Empirical relations identifying volume required | Czysz[52] |

TABLE 4.3 – Summary of methods used in the X-20 MDA

that iterated for every combination of planform and wing-loading. It is noted that there is a total of 201 variables involved in one sizing iteration when including those internally used within the disciplines, see



SINGLE DESIGN POINT

Design Summary

| | | | |
|---|---|---|---|
| S_pln | 29.93 | m^2 | Independent Variable |
| W/S | 1470.7 | N/m^2 | |
| TOGW | 44014 | N | Weights |
| W_str | 13966 | N | |
| OWE | 42931 | N | |
| l | 8.9 | m | Geometry |
| b | 5.65 | m | |
| S_Wet | 144.6 | m^2 | |
| V_tot | 37.66 | m^3 | |
| L/D hyp | 2.2 | | Performance |
| CrossRange | 2133 | km | |
| DownRange | 33382.3 | km | |

Mission Constraints

| | |
|---|---|
| # Crew | 1 |
| W_cargo | 450 kg |

FIGURE 4.30 – Single Design Point Solution is obtained by iterating on $S_{pln}$ and $W/S$ while converging on Weight and Volume.

Figure 4.31. Given the large quantity of data available, it is impractical to illustrate and discuss all results. Therefore, only the most significant variables that represent the overall design solution and provide a holistic representation of the case-study are presented. The following sections address these primary design drivers.

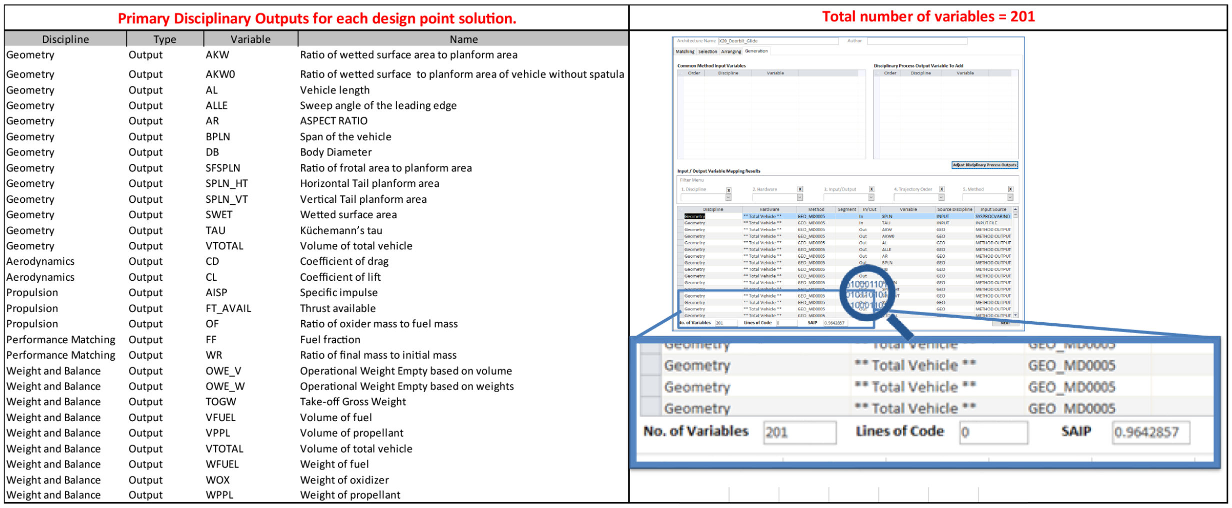
### Multi-point Design Solution Space

As mentioned before, the Küchermann slenderness parameter $\tau$ along with planform area defines and controls the overall geometry properties of the vehicle[90]. For a single point design solution, planform area is iterated along with wing loading to converge the sizing process. Further iteration on $\tau$ and other mission parameters populates a solution space consisting of individually converged total vehicle design points. The overall design solution space provides a carpet plot visual aid that is of significant value for the decision maker during the early design phase. Figure 4.32 shows the overall solution space generated for the X-20 vehicle by iterating on $\tau$ and Crew size.

As seen in the figure, the carpet plot consists of a total of 63 design points where each vehicle is a converged solution similar to the case shown in the previous section. Every design point accounts for approximately 200 variables and produces 27 disciplinary outputs. Additionally, both the X-20 glider and the glider with tran-stage lie within the solution space. Further, it can be seen that the X-20 glider lies on the $\tau = 0.22$ line and slightly above the crew size equal to one case. The closest design point sized to the mission constraints of the original X-20 glider is also recognized on the carpet plot. This nodal point on the carpet plot is the closest solution concept to the original that was sized in the multi-point iteration.

### Constraint implementation

Following the generation of the solution space carpet plot, the next step is to identify the limiting constraints that define the feasible design options. Two principle constraints are considered; they are max



Primary Disciplinary Outputs for each design point solution.

| Discipline | Type | Variable | Name |
|---|---|---|---|
| Geometry | Output | AKW | Ratio of wetted surface area to planform area |
| Geometry | Output | AKW0 | Ratio of wetted surface to planform area of vehicle without spatula |
| Geometry | Output | AL | Vehicle length |
| Geometry | Output | ALLE | Sweep angle of the leading edge |
| Geometry | Output | AR | ASPECT RATIO |
| Geometry | Output | BPLN | Span of the vehicle |
| Geometry | Output | DB | Body Diameter |
| Geometry | Output | SFSPLN | Ratio of frotal area to planform area |
| Geometry | Output | SPLN_HT | Horizontal Tail planform area |
| Geometry | Output | SPLN_VT | Vertical Tail planform area |
| Geometry | Output | SWET | Wetted surface area |
| Geometry | Output | TAU | Küchemann's tau |
| Geometry | Output | VTOTAL | Volume of total vehicle |
| Aerodynamics | Output | CD | Coefficient of drag |
| Aerodynamics | Output | CL | Coefficient of lift |
| Propulsion | Output | AISP | Specific impulse |
| Propulsion | Output | FT_AVAIL | Thrust available |
| Propulsion | Output | OF | Ratio of oxider mass to fuel mass |
| Performance Matching | Output | FF | Fuel fraction |
| Performance Matching | Output | WR | Ratio of final mass to initial mass |
| Weight and Balance | Output | OWE_V | Operational Weight Empty based on volume |
| Weight and Balance | Output | OWE_W | Operational Weight Empty based on weights |
| Weight and Balance | Output | TOGW | Take-off Gross Weight |
| Weight and Balance | Output | VFUEL | Volume of fuel |
| Weight and Balance | Output | VPPL | Volume of propellant |
| Weight and Balance | Output | VTOTAL | Volume of total vehicle |
| Weight and Balance | Output | WFUEL | Weight of fuel |
| Weight and Balance | Output | WOX | Weight of oxidizer |
| Weight and Balance | Output | WPPL | Weight of propellant |

Total number of variables = 201

| | | |
|---|---|---|
| Geometry | ** Total Vehicle ** | GEO_MD0005 |
| Geometry | ** Total Vehicle ** | GEO_MD0005 |
| Geometry | ** Total Vehicle ** | GEO_MD0005 |

No. of Variables: 201
Lines of Code: 0
SAIP: 0.9642857

FIGURE 4.31 – Total number of internal and external variables involved in a single point convergence.

heat flux and TPS, and lift-off vehicle max payload. These constraint limits are implemented and visualized in Figure 4.33.

The constraints for maximum heat flux during the equilibrium glide section of the trajectory is provided by Glaman[88] in terms of the wing loading and nose radius, see equation 4 in Galman[88]. The TPS technology level identifies the constraining regions. When assuming the thermal protection system technology level of the Space Shuttle[95],it provides a wider valid region than the solution space, thus it does not affect the current developed solution design space for the X-20. Assuming a reduced technology level, one equivalent to that of the X-20 program era, it can be seen in figure 4.33 that the solution space decreases significantly. The TPS technology level limits the feasible design space to a max crew size of 3 and $\tau = 0.23$.

The second constraint is recognizing the payload limit of the Titan-IIIC launch vehicle. The Titan-IIIC was selected as the primary launch vehicle for the X-20 glider in the early 1960s[31]. The Dyna-Soar program was canceled before the first flight of the launch vehicle. As can be seen clearly from Figure 4.33, the launch vehicle ability also reduces the overall solution space significantly. However, although the feasible design solution space reduces significantly after application of those constraints, both configurations, the X-20 glider and the glider with trans-stage, still lie comfortably in the feasible design space. The second phase of the X-20 program was planned with a higher performing mission profile and increased crew member capacity. Consequently, vehicles of this increased payload capability would not lie in the solution space shown with Figure 4.32 and 4.33.

It is important to mention again that the X-20 program was the first

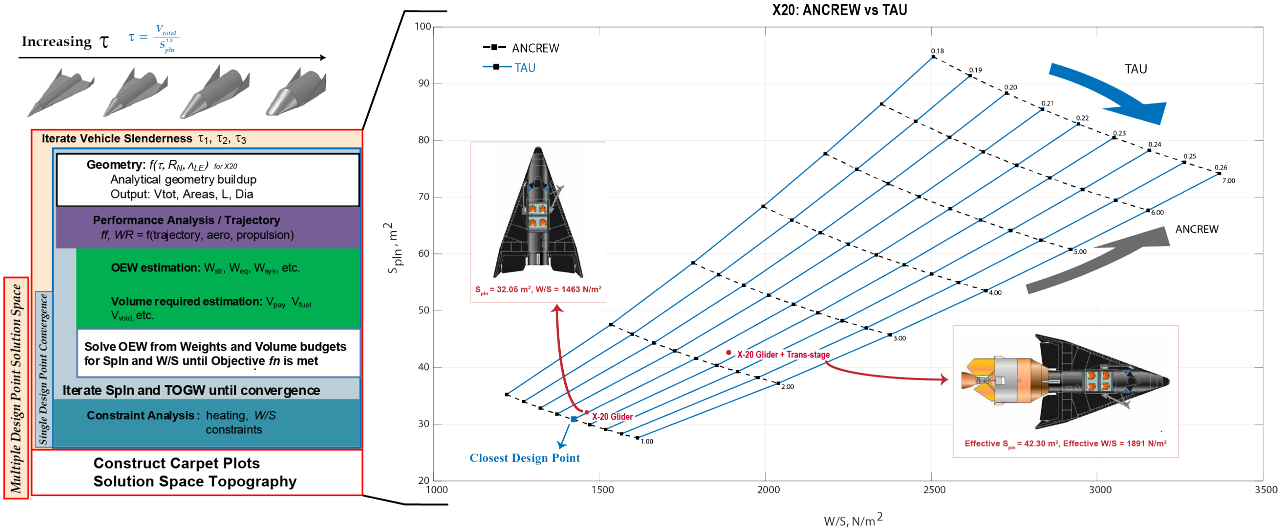


FIGURE 4.32 – Single Design Point Solution is iterated for $\tau$ and other mission parameters for developing a design solution space. Each design point is a converged vehicle solution concept.

large scale industrial-level program for the development of an operational LRV vehicle and occurred more than two decades before the first flight of the STS. Most of the technology, knowledge, data, and even the test-facilities developed during the X-20 program found application in the follow on generations of lifting body programs, eventually leading to the development of the Space Shuttle. This is further confirmed by several noted authors, historians, and researchers[31, 75, 95–98] as almost every account of the history and development of the STS program mentions the X-20 program as a major contributor towards the Space Shuttle vehicle.

The X-20 was the pathfinder for its time that produced invaluable data and knowledge. Multiple new technologies were developed during the life-time of the X-20 to successfully develop the first operational LRV. Sadly, that had to wait for more than 20 years owing to political reasons. Geiger states; *"the X-20 Dyna-Soar died not from technical insufficiency but from political disfavor."[31]*. Houchins further confirms and adds to the impact of the cancellation of the X-20 program: "Dyna-Soar was not a technological failure. It could have flown. On the other hand, Dyna-Soar's cancellation marked the collapse of the Air Force's political-economic efforts for a hypersonic boost-glider, illustrating the need for a rapid and clear consensus of purpose, single-minded and politically astute leadership, and the near-term attainment of advanced technology."[97]. Both Geiger and Houchins present detailed and well-documented accounts of the complicated political-economic circumstances leading to the cancellation of the X-20 program and its impact on the space industry had it been developed during the 1960s.

The present study further reestablishes the feasibility of a forgotten

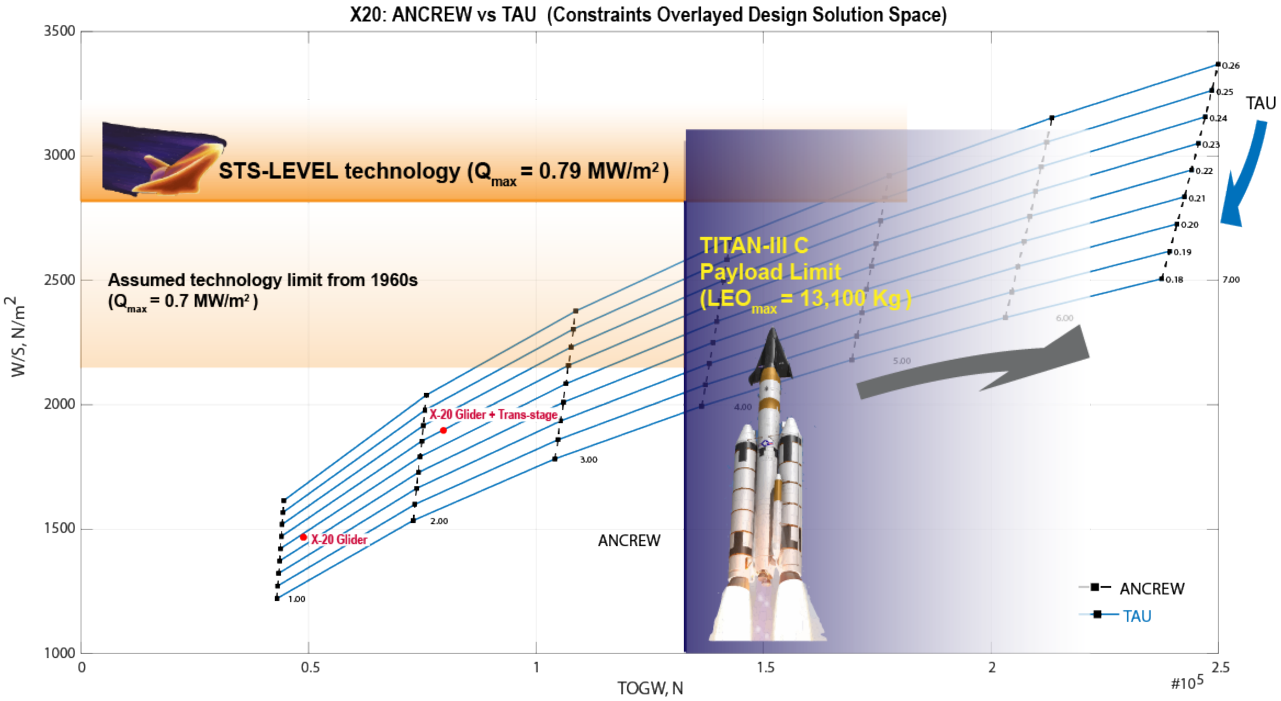


FIGURE 4.33 – Constraints applied based on TPS system technology and LV weight constraints.

program through a parametric assessment of the technical feasibility and advanced capability the X-20 could have provided. This could have helped the industry leapfrog historical progress had the administration provided the required timely support. In this account, the X-20 presents a case-study that the present generation of planners and designers need to acknowledge and learn in order to avoid making the same mistakes which could possibly result, again, in a potential decline of the current re-usability space progress, the likes of which was experienced through the decades following the Apollo program.

### 4.4.2 *Generic Case-1: The Lifting Bodies*

The X-20 case-study shows the capability of AVD$^{SIZING}$ to effectively converge the multi-disciplinary framework and size a vehicle concept that is physically feasible and meets the required mission objectives. Further, the X-20 case-study also shows how the system is used to perform sweep on $\tau$ to develop a solution space continuum containing infinite converged vehicles while trading on a mission parameter (number of crew in the X-20 case) to size multiple converged vehicles. The constraint implementation is used to define the feasible design space. This case-study thus shows the power of the highly modular and customizable synthesis system to effectively explore the design solution space along all three primary trade dimensions. Figure 4.34

is repeated here from first Section to remind the reader of the primary trade dimensions. This figure is a found to be a significant visual tool to realize the real scale of the infinite possibilities that could be explored in the conceptual design phase.

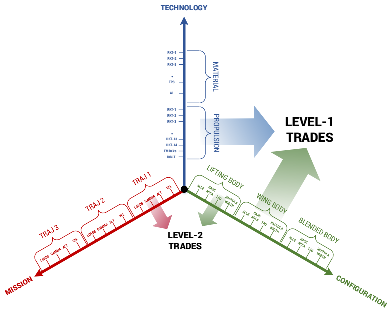


FIGURE 4.34 – Complete overall trade-matrix showing primary and secondary trades

This case-study thus defines a generic configuration in an attempt to cover some of those possibilities and show numerically how the true scope of the CD phase is often gone unnoticed to a specialist who is not involved in the primary exploration phase of the design environment.

## CASE-STUDY DESCRIPTION

Lifting body configuration represents a class of geometry that has the same generic shape but can have various geometry profiles by variations in geometry parameters like the shape of the base-area, flat/round bottom, leading-edge angles etc. A first order assessment of the sensitivities of general shape parameters of the vehicle on the final vehicle performance is a powerful capability attribute to this multidisciplinary sizing methodology and implementation. This study demonstrates this effect of the general shape and geometric parameters' trades along with other two trade dimensions. The possible geometric variations for a generic lifting body configuration and how they are applied to create specific geometry profiles are shown in Figure 4.35.

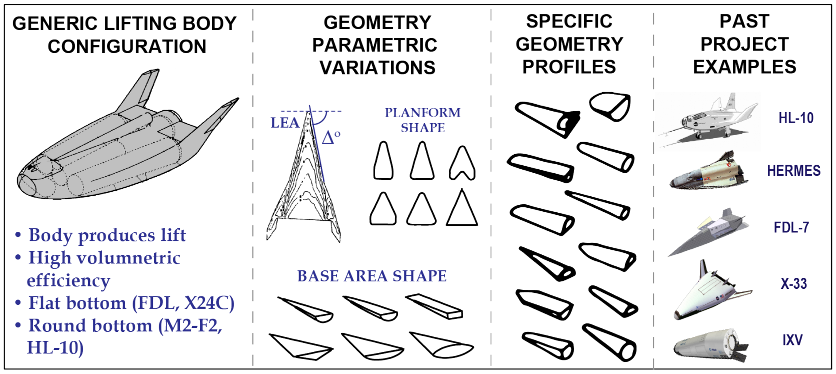


FIGURE 4.35 – Parametric variations in generic lifting body configurations and development of specific geometry profiles.

**GEOMETRY PROFILES, MDA AND DISCIPLINARY METHODS** The geometry profiles are developed using analytical and empirical analysis methods to calculate the overall geometric properties of the vehicle. The geometry analysis is the first discipline that defines the overall shape of the vehicle which is then used to calculate its aerodynamics and execute further disciplines. Two distinct methods are used to define the geometry as per the characteristic of the vehicle.

Czysz[52],[90] provides analytical relationships between various geometric parameters that are used to define a series of geometry profiles with varying base-area for lifting bodies. The parametric geometric relationships provided by Czysz are limited to a planform leading edge angle of 78 degrees which is a correct sweep angle for reentry gliders.

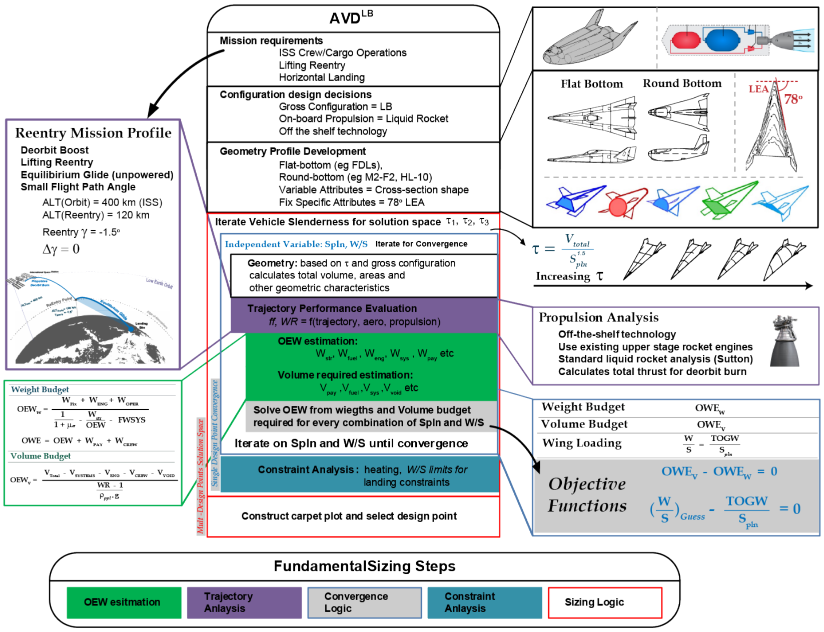


FIGURE 4.36 – Fundamental logic of the sizing methodology executed in AVD$^{LB}$ MDA framework.

OpenVSP is utilized as the second primary geometry generation tool as it provides a flexible platform to build parametric geometries. The process of building a geometry configuration begins with selecting the desired configuration and the lifting body is the selected primary configuration chosen for the present study. Then a cross section shape is chosen and a fixed model is generated. Both the processes are described in detail earlier in the Section 4.3.2, *'Technology Requirements'*.

Following the geometry profiles creation, an integrated synthesis procedure is developed along the line of the sizing logic of the AVD$^{SIZING}$ with generic lifting body configuration shape, see Figure 4.36. Each geometry profile is executed through the MDA framework, solving for primary design-disciplines of aerodynamic, propulsion, performance, trajectory, and weights calculations, as discussed previously in Section 4.3.3. The analysis methods for involved disciplines is similar to the X-20 disciplinary methods. Table 4.4 provides a summary of the involved disciplinary methods.

### TRADE MATRIX IMPLEMENTATION

The X-20 case-study addressed a legacy vehicle design which had a fixed geometry configuration with fixed mission objectives and technology requirements. Contrary to that, the generic LB geometry case-

| Discipline | Application | Description | Reference |
|---|---|---|---|
| Geometry | | | |
| | LB Generic Configuration | Hypersonic Convergence and OpenVSP methods implemented for execution of geometry parameters trades | Czysz[52] |
| Aerodynamics | | | |
| | Subsonic, Supersonic, and Hypersonic | Empirical McDonald Douglas aerodynamic relations for estimating lift-to-drag ratio $(L/D)_{max}$, lift curve slope $C_{L_\alpha}$, induced drag factor $L'$, and zero lift-drag coefficient $C_{D_o}$ | HyFac[94],<br>Coleman[27] |
| Propulsion | | | |
| | Rocket Performance | Off and on design point analytical relations for determination of $I_{sp}$ and thrust available $T$ | Sutton[91] |
| Performance Matching | | | |
| | De-Orbit | Analytical relation for the de-orbit problem identifying $\Delta V$ and entry velocity, $V_e$, as a function of entry flight path angle, $\gamma_e$ and de-orbit parking orbit $r_p$ | Low[85] |
| | Cross-Range | Analytical relation for cross-range determination as a function of a constant optimum bank angle $\phi_{opt}$ and $L/D$ | Vinh[86] |
| | Down-Range | Analytical relation for determination of max down-range as a function of $L/D$ and atmospheric starting glide velocity | Galman[88] |
| | Glide | Relations for small flight path angle glide from re-entry to landing | Miele[87] |
| Aerothermodynamics | | | |
| | Max Heat Flux | Max heat flux correlation as a function of glide weight $W$, coefficient of lift $C_L$, planform area $S_{pln}$, and nose radius $r_N$ | Galman[88] |
| Weight and Volume | | | |
| | Weight | Empirical relations for the identifying of weight contributions | Czysz[52] |
| | Volume | Empirical relations identifying volume required | Czysz[52] |

TABLE 4.4 – Summary of methods used in the X-20 MDA

study provides a wide range of design solutions which are addressed here. While the X-20 design point was iterated on $\tau$ and number of crew to explore the X-20 design solution space and mission capability range, the LB configuration is assessed for fixed mission objectives of 1 crew member and a fixed payload of 450 kg (the payload of the X-20 mission). Then, a range of other trades are all applied to the geometry configuration, mission trajectory variables, and technology trades (by changing the rocket engine and fuel type). This execution study covered a large range of trades that finally resulted in an enormous solution space of **636 converged design concepts**. It must be noted here that each design point has been sized in a similar manner as described in the single point design convergence of the X-20 case-study. That is, each design point has been iterated for planform and wing loading until the convergence criteria was met. Clearly, every design point is a converged design concept that calculated more than 200 internal and external disciplinary variables where each has around 30 disciplinary outputs.

The overall trade space description is provided in the Table 4.5. As shown in the table, a $\tau$ sweep serves as the primary trade variable for volumetrically scaling the vehicle shape, while the other trade parameters are defined specifically based on the constraints of the disciplinary methods and execution capability and data-handling capacity of the software (MATLAB, OpenVSP etc.). The iteration variables are shown with the range of iteration while the number in the brackets denotes the number of steps of the iteration for the specific variable[11]. Every trade study is first developed as an independent architecture in the AVD-DBMS which provides a MATLAB executable sizing code of several MATLAB scripts. These are patched together by the variables connection specified in the DBMS. The trades definition is specified in the primary input file in the MATLAB code structure based on how the architecture was setup in the DBMS.

The following section now describes the results and discussion of the trade space execution.

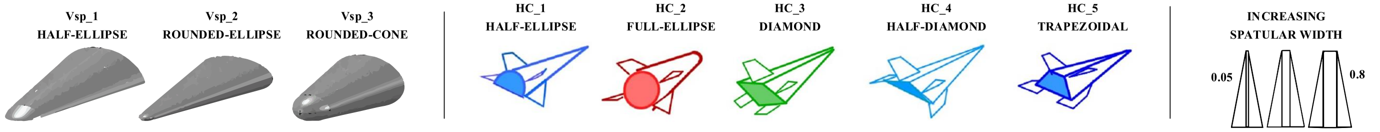
## Results Interpretation

As mentioned earlier, a large amount of data has been generated from the LB case-study. A total of 636 converged design solutions emerged out of the study, where each design point has calculated around 200 variables and every trade study has been an independent architecture execution. The common aspect of all the 636 converged vehicles is the underlying mission objective, since all of the architectures have been executed to carry 1 crew member and 450 kg of payload mass for a LEO reentry mission.

The results obtained until this point in the GDSP solution process are representative of the execution of the first three steps. The *Mission Analysis*, *Technology Requirements,* and *Hardware Selection* steps have been executed at this point, and the hardware specification for *636*

[11] For example, as seen in the first column TAU range is 0.14 - 0.3 while (8) denotes the number of iteration of TAU

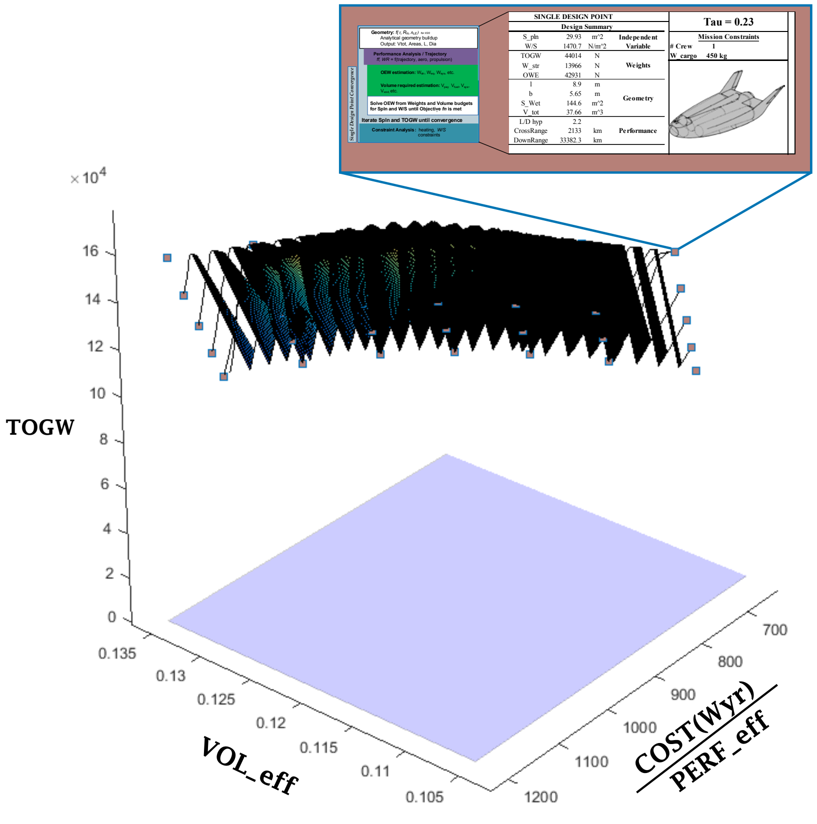
**GEOMETRY TRADES**



| | LIFTING BODY CONFIGURATION | | | | MISSION | | TECHNOLOGY | # | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **TRADE STUDIES** | TAU | BASE-AREA | Δ (Leading Edge) | SPATULA WIDTH RATIO | REENTRY ALTITUDE | ORBITAL OPS DELTA-V | ENGINES | **CONVERGED DESIGN PTS.** | **COMMENTS** | **WHAT WAS EXPLORED** |
| **Trade Study 1**<br>**VSP Geometry Trade** | 0.14 - 0.3 (8) | VSP_1 - VSP_3 (3) | Fixed (78 deg) | 0 | Fixed (120 km) | 0 | Eng11 (LOX/LH2) | **24** | Geoemetry variation using VSP Model | How changing geometry LEA of various base shapes affect overall design solution |
| **Trade Study 2**<br>**VSP Geometry Trade** | 0.14 - 0.3 (8) | VSP_1 - VSP_3 (3) | Fixed (76 deg) | 0 | Fixed (120 km) | 0 | Eng11 (LOX/LH2) | **24** | Geoemetry variation using VSP Model | How changing geometry LEA of various base shapes affect overall design solution |
| **Trade Study 3**<br>**VSP Geometry Trade** | 0.14 - 0.3 (8) | VSP_1 - VSP_3 (3) | Fixed (74 deg) | 0 | Fixed (120 km) | 0 | Eng11 (LOX/LH2) | **24** | Geoemetry variation using VSP Model | How changing geometry LEA of various base shapes affect overall design solution |
| **Trade Study 4**<br>**VSP Geometry Trade** | 0.14 - 0.3 (8) | VSP_1 - VSP_3 (3) | Fixed (72 deg) | 0 | Fixed (120 km) | 0 | Eng11 (LOX/LH2) | **24** | Geoemetry variation using VSP Model | How changing geometry LEA of various base shapes affect overall design solution |
| **Trade Study 5**<br>**Geometry Trade with Spatula** | 0.14 - 0.34 (8) | HC_1 - HC_5 (5) | Fixed (78 deg) | 0.05 - 0.8 (3) | Fixed (120 km) | 0 | Eng11 (LOX/LH2) | **120** | Geometry Variation of #5 Hyp Cpnv Base-Shapes and Width of Spatula | How adding spatula to various geometry base shape affect overall design solution |
| **Trade Study 6**<br>**Geometry and Mission** | 0.14 - 0.315 (7) | HC_1 - HC_5 (5) | Fixed (78 deg) | 0 | 130 - 170 km (4) | 0 | Eng11 (LOX/LH2) | **140** | Combined Trade of Mission Reentry Altitude with Base Area Shapes | How does reentry altitude affect overall design solution for different base shapes |
| **Trade Study 7**<br>**Geometry and Mission** | 0.16 - 0.3 (7) | HC_1 - HC_5 (5) | Fixed (78 deg) | 0 | Fixed (120 km) | 0 - 25 (km/s) (5) | Eng11 (LOX/LH2) | **175** | Combined Trade of Mission Operations in Orbit with Base Area Shapes | How extra fuel for orbital ops affect design solution of various base shape |
| **Trade Study 8**<br>**Geometry and Technology** | 0.14 - 0.315 (7) | HC_1 - HC_5 (5) | Fixed (78 deg) | 0 | Fixed (120 km) | 0 | Eng11 (LOX/LH2),<br>Eng12(LOX/UDMH),<br>Eng13(N2O4/UDMH) (3) | **105** | Combined trade of Base Area with different engines of different fuel type | How does various base shapes perfrom with different engines and fuel types |
| **TOTAL NUMBER OF CONVERGED DESIGN POINTS EXPLORED FOR VARIOUS TRADES OF CONFIGURATION, MISSION AND TECHNOLOGY** | | | | | | | | **636** | | |

TABLE 4.5 –
Overall Trade space description of the 636 converged design solutions for the generic LB case-study.

feasible design concepts has been obtained. The next step then implements the execution of the *Cost-per-Performance* analysis, where the total cost for all 636 vehicles has been calculated following the methodology described earlier.



| SINGLE DESIGN POINT | | | |
|---|---|---|---|
| Design Summary | | | |
| S_pln | 29.93 | m^2 | Independent Variable |
| W/S | 1470.7 | N/m^2 | |
| TOGW | 44014 | N | Weights |
| W_str | 13966 | N | |
| OWE | 42931 | N | |
| l | 8.9 | m | Geometry |
| b | 5.65 | m | |
| S_Wet | 144.6 | m^2 | |
| V_tot | 37.66 | m^3 | |
| L/D hyp | 2.2 | | Performance |
| CrossRange | 2133 | km | |
| DownRange | 33382.3 | km | |

FIGURE 4.37 – Results Visual showing measuring variables.

Since every architecture is executed independently, the result for every architecture is stored in a MATLAB data file which has all the primary design data for all the vehicles sized under the respective trade study. Once the converged sizing results are obtained, the output MATLAB file is executed as a structured data-set for a series of equations which is called the post-processing. This post-processing is concerned with the total cost and the derived performance calculation. The performance efficiency factor, the volumetric efficiency and the others are calculated here as the overarching representative of the holistic measure of each vehicle. These efficiency factors along with a few primary variables like take-off gross weight (TOGW) etc are then extracted from each architecture and assembled together for the definition of an overarching solution space. Three dimensional plotting is found to be the most effective visual aid where three (or four) of these significant variables can be compared simultaneously thus providing

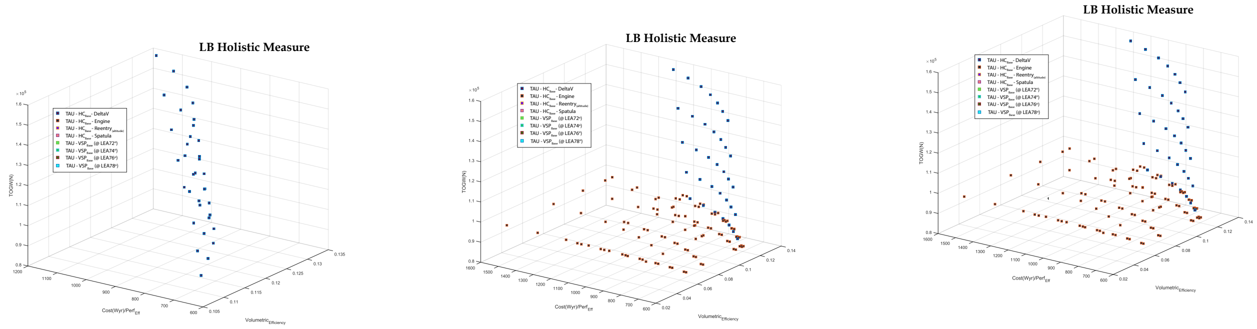


FIGURE 4.38 – Parametric variations in generic lifting body configurations and development of specific geometry profiles.

a holistic comparison capability for a consistent comparison for all 636 vehicles simultaneously.

First, a demo of the result is shown in Figure 4.37 which contains data for only one trade study, where the three measuring axis are visualized, and the individual design points are shown. The plots are overlayed over the same axis as seen in the Figure 4.38.

The final results for all the trade-studies are now plotted together in one continous solution space. This solution space contains data for all 636 converged design solutions. The best solution based on the three axis would be the one that has the least weight (TOGW), maximum volumetric efficiency and least cost/performance (note that Cost/Per$_{eff}$ is the inverse of Perf/Cost which is same as miles-per-gallon or miles-per-dollar number for road vehicles). It can be seen that vehicles sized by the OpenVSP geometry method with a 78 degree leading edge angle are most favorable on these measures.

Figure 4.39 shows the results for all vehicles combined where the best design point identified on all three measures corresponds to an elliptical LB body with 78 degree leading edge angle.

### 4.4.3 *Generic Case-2: The Wing Bodies*

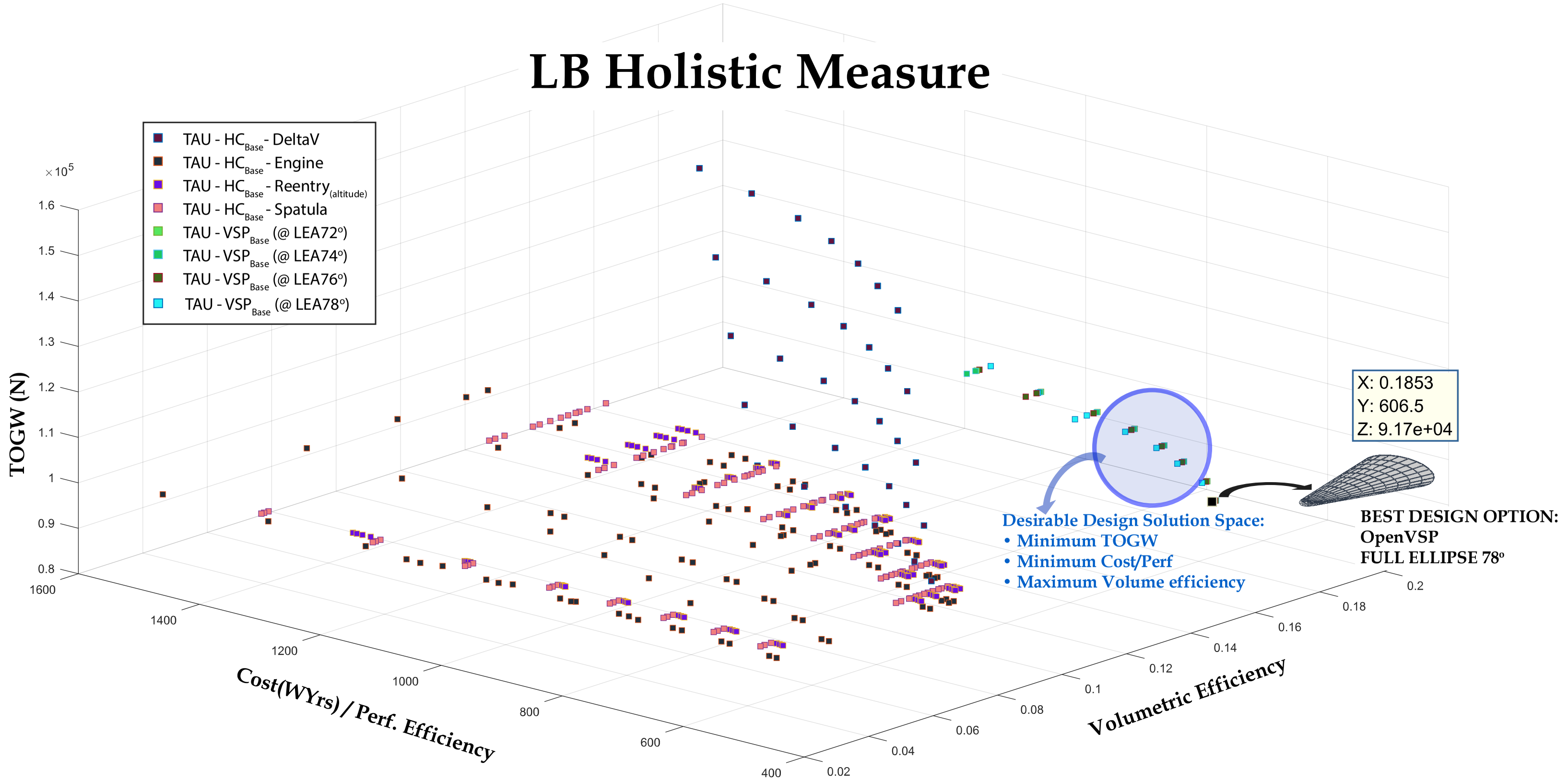


FIGURE 4.39 –
Overall Trade space description of the 636 converged design solutions for the generic LB case-study.

Similar to the generic LB case-study, an exploratory case was executed for the generic wing-body configuration as well. Three different WB geometry configuration profiles are created using OpenVSP geometry method, see Figure 4.40. The MDA logic and the disciplinary methods used were same as the the LB case-study.

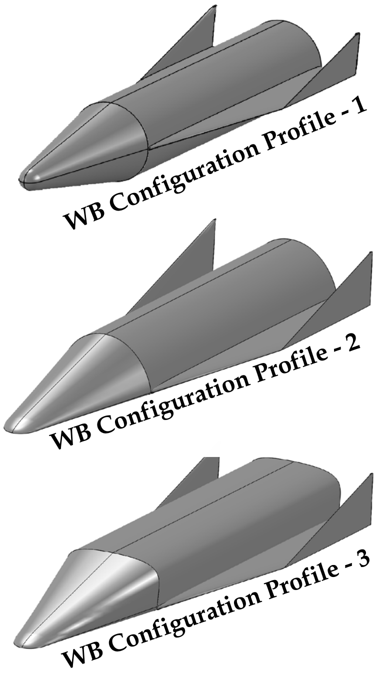


FIGURE 4.40 – WB Configuration profiles created using OpenVSP

### Trade Matrix Implementation

The geometry trades conducted are for vehicle configuration profile and leading edge angle (LEA). A technology trade is performed through the variation of fuel and oxidizer type. This is achieved by selecting an off-the-shelf engine from the engine deck as explained in the propulsion discipline description. Each trade study and the corresponding details are summarized in Table 4.6. Note that the range of $\tau$ and leading edge angles are dependent on the constraints implemented by the geometry profile shape and OpenVSP model. The variation of the ranges is primarily due to the numerical limitation of the geometric solver in VSP analysis script. Although the maxima and minima of the $\tau$ and LEA are different, the number of steps for both in all geometric iterations are the same. The **total number of design points sized for this study are 540** as shown in the Table 4.6. Each of these points is a converged design solution which is executed by a iteration of planform and wing laoding area as explained above. Thus a huge amount of data was generated for primarily three geometry profiles. This is addressed in the next section.

### Results

Following the sizing of all 540 single point design solution a design solution continuum is prepared that addresses the overall bigger picture configuration level solution space. This is different from the individual design-points solution space obtained by trading tau and planform since here several inherently different design options are considered. Figure 4.41 shows example of a design solution continuum for geometry profile 2 with all trades of engines and reentry altitudes.

The overall solution space continuum as shown in the Figure 4.42 the effect of certain trades on the three performance metrics. The relationship between wing loading and structural weight is positive and increasing with a distinct difference between two sets of data which correspond to different engines using different fuel types. Rotation of the solution space to show the performance index reveals that not all points along those lines are equal and there is a wide spread of performance related to engine ISP, L/D and reentry velocity. The range of values for each vehicle shape are also different (denoted by color)

| | LIFTING BODY CONFIGURATION | | | MISSION | TECHNOLOGY | # CONVERGED DESIGN PTS. |
|---|---|---|---|---|---|---|
| | TAU | Leading Edge Angle | WB Configuration Profile | REENTRY ALTITUDE | ENGINES | |
| **Trade Study 1**<br>**VSP Geometry and Technology** | 0.083-0.107 (5) | Fixed(66 deg) | 1 | 140 km - 95 km (4) | Eng 11 (LO2/LH2), Eng 12 (LO2/LH2), Eng 13 (N2O4/UDMH) | **60** |
| **Trade Study 2**<br>**VSP Geometry and TechnologyTrade** | 0.084-0.104 (5) | Fixed(68 deg) | 1 | 140 km - 95 km (4) | Eng 11 (LO2/LH2), Eng 12 (LO2/LH2), Eng 13 (N2O4/UDMH) | **60** |
| **Trade Study 2**<br>**VSP Geometry and TechnologyTrade** | 0.09-0.114 (5) | Fixed(70 deg) | 1 | 140 km - 95 km (4) | Eng 11 (LO2/LH2), Eng 12 (LO2/LH2), Eng 13 (N2O4/UDMH) | **60** |
| **Trade Study 4**<br>**VSP Geometry and TechnologyTrade** | 0.11-0.178 (5) | Fixed(72 deg) | 2 | 140 km - 95 km (4) | Eng 11 (LO2/LH2), Eng 12 (LO2/LH2), Eng 13 (N2O4/UDMH) | **60** |
| **Trade Study 5**<br>**VSP Geometry and TechnologyTrade** | 0.092-0.16 (5) | Fixed(75 deg) | 2 | 140 km - 95 km (4) | Eng 11 (LO2/LH2), Eng 12 (LO2/LH2), Eng 13 (N2O4/UDMH) | **60** |
| **Trade Study 6**<br>**VSP Geometry and TechnologyTrade** | 0.09-0.13 (5) | Fixed(78 deg) | 2 | 140 km - 95 km (4) | Eng 11 (LO2/LH2), Eng 12 (LO2/LH2), Eng 13 (N2O4/UDMH) | **60** |
| **Trade Study 7**<br>**VSP Geometry and TechnologyTrade** | 0.082-0.13 (5) | Fixed(68 deg) | 3 | 140 km - 95 km (4) | Eng 11 (LO2/LH2), Eng 12 (LO2/LH2), Eng 13 (N2O4/UDMH) | **60** |
| **Trade Study 8**<br>**VSP Geometry and TechnologyTrade** | 0.085-0.133 (5) | Fixed(72 deg) | 3 | 140 km - 95 km (4) | Eng 11 (LO2/LH2), Eng 12 (LO2/LH2), Eng 13 (N2O4/UDMH) | **60** |
| **Trade Study 9**<br>**VSP Geometry and TechnologyTrade** | 0.082-0.11 (5) | Fixed(76 deg) | 3 | 140 km - 95 km (4) | Eng 11 (LO2/LH2), Eng 12 (LO2/LH2), Eng 13 (N2O4/UDMH) | **60** |
| **TOTAL NUMBER OF CONVERGED DESIGN POINTS EXPLORED FOR VARIOUS OF CONFIGURATION, MISSION, AND TECHNOLOGY** | | | | | | **540** |

TABLE 4.6 – Different trade studies investigated

which is attributed to a difference in feasible tau ranges for each shape. This is a feature of a geometry type and cannot be greatly influenced by modifying the geometry i.e. a cylinder has higher volumetric efficiency than a half cylinder.

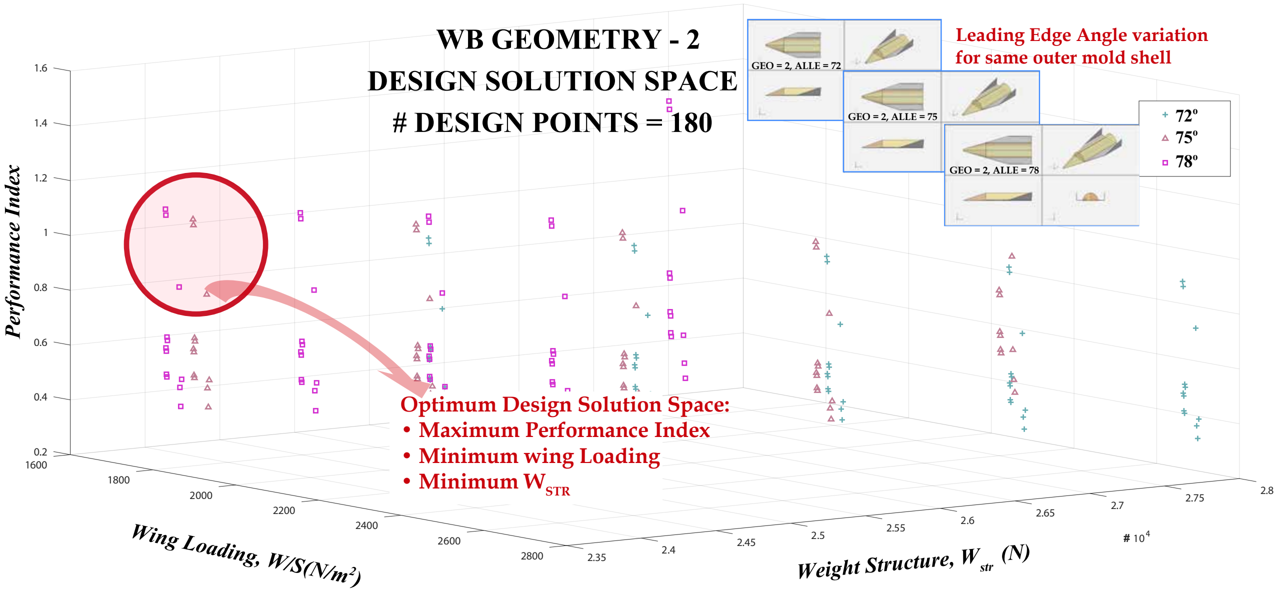
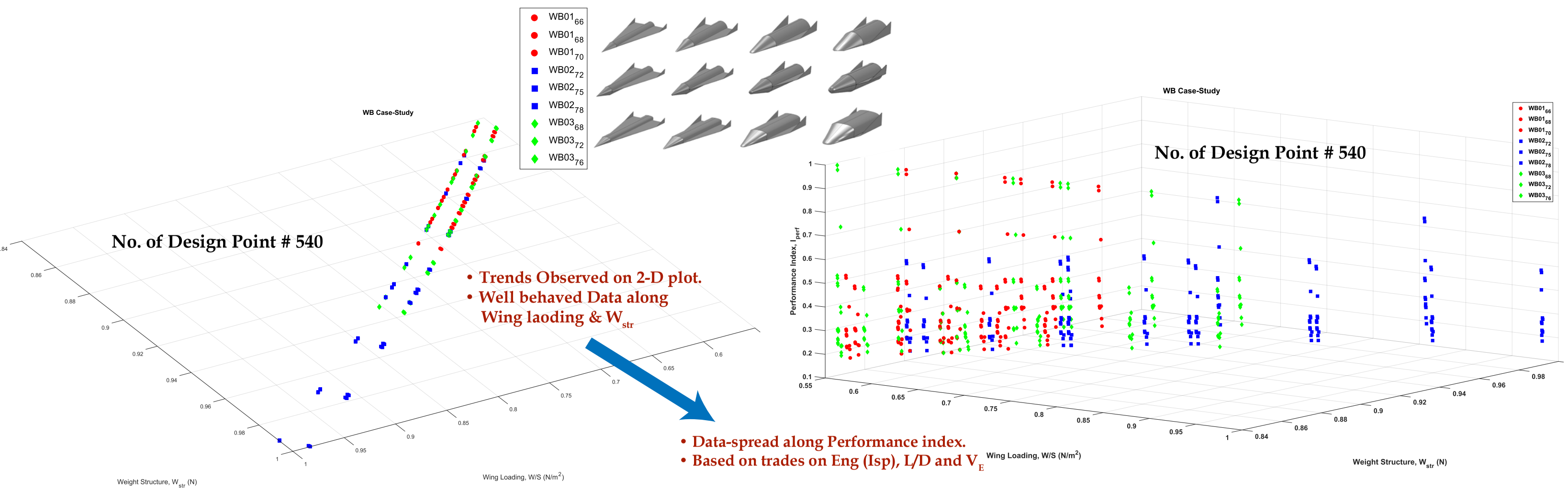


FIGURE 4.41 – Creation of overall solution space for a geometry profile. Similar design solution continuum is generated for all three geometry profiles.

When examining the specific wing body geometry solution space, there exist an optimal solution at the minimum wing loading, structural weight and highest performance index. This area is denoted by the red circle and is populated by both 78 degree and 75 degree leading edge angle vehicles. The highest performance is associated with the 78 degree leading edge although this solution space shows that the 75 degree vehicles are not much further away and could be an alternative if further studies show an advantage to lower angles. There are higher performance index vehicles but at the cost of much higher wing loading and structural weight seen in the middle of the solution space. Determining if the extra performance is worth the extra weight and wing loading depends on the decision drivers and required margins.

### 4.4.4 *Summary*

This chapter has demonstrated the application of the SAS-GDSP solution to the LRV class of SAVs. Three case-studies are executed and the final results are shown in the powerful design solution space topography which contains a vast number of individual design points. Trades on all three primary dimensions of *Technology-Configuration-Mission* have been conducted. To consistently measure such a large



- Trends Observed on 2-D plot.
- Well behaved Data along Wing laoding & $W_{str}$

- Data-spread along Performance index.
- Based on trades on Eng (Isp), L/D and $V_E$

FIGURE 4.42 –
Overall solution space continuum for 540 converged WB design points. A well behaved trend is seen in 2-D view primarily due to the choice of propulsion system. A more distributed data-spread is seen along performance axis.

number of design options, hollistic performance indices are defined which serve as the overarching parameters and provide an hollistic comparison amongst the various options.

This type of solution spaces are significant during the CD phase assessment as they provide the decision maker with the capability to rapidly scan across the feasible design solutions landscape and select a region of specific design concepts.

Chapter 5

# PHYSICAL SOLUTION ARCHITECTURE IMPLEMENTATION OF THE SAS-GDSP FOR TSTO-VTHL AT HIERARCHY LEVEL 1

The VTHL class of SAS is a compound system, made up of vertically launching ballistic rockets and horizontally landing lifting reentry vehicles . The LRVs have been sized following the SAS-GDSP solution by implementing the AVD-DBMS platform introduced in Chapter 4. This has established the applicability of the solution at the second hierarchy level of the SAS where the two SAV types (LRVs and LVs) do exist. Now, this chapter applies the generic SAS-GDSP solution to the SAS level for the VTHL class.

## 5.1 The VTHL Case-Study

The VTHL type SAS class selected for this research investigation is the TSTO case where the LV and the RV are two separate systems. As previously justified Chapter 1[1], this decision has been primarily based on the historical trends observed and the current state of the industry. The following reasons were identified as the primary motivation for selection of a TSTO-VTHL system:

- SSTO-SAS are not feasible with the current state of technology. Lessons from past projects show that this category requires extensive additional R& D effort and a paradigm shift in several technologies.
- Horizontal launch systems share similar drawbacks to SSTO-SAS and they are not the most economically feasible near-term solution.
- Partially reusable vertical launch vehicles are currently under development with a tremendous growth rate. They are causing market disruption and may prove to be cost effective. These systems are on a faster trajectory to achieve full system reusability than developing a SSTO launch system.
- Legacy ballistic reentry vehicles are simpler to design and manufacture, but they show restricted overall performance and limited mission operations capabilities.

[1] see Section 1.2.2

- Lifting reentry vehicles are high performance vehicles with a vast range of mission capabilities. These vehicles perform horizontal landing on a runway and are most suitable candidate for tourism and commercial market of the future. Additionally, LRVs have been study extensively in the past and are currently being investigated by space entities all over the globe.

Livingston[14], Andrews et al[15] and Diessel et al[16] in the past studies provide comparative assessments of horizontal and vertical launch modes showing that the vertical launch mode is the preferred mode considering near-term launch capability. Dissel concludes,"if a near-term launch capability is desired, the fully reusable TSTO rockets are close competitors with the airbreathing vehicles and are the next logical improvement over current rocket launch systems."[16]

Additionally, the recent success of the commercial company SpaceX in successfully reusing just the first stage of a vertical launch rocket booster makes the vertically launching rocket boosters as even more lucrative option. Considering these facts, a TSTO-VTHL system appears to be the next logical step towards achieving a fully reusable SAS.

Thus, the TSTO-VTHL systems addressed in this chapter are composed of the vertically launched LVs and the horizontally landing LRV vehicles (that are sized in the previous chapter) as the building blocks for the top-most SAS level. The considered LVs are discussed next, and are representative of existing or near future LV capability.

### 5.1.1 *Selection of the LV types*

The launch vehicles cases are selected based on the current technology availability and are composed of the existing or assumed to be developed in near future launch elements. The base elements for the LVs are the constituting stages. The industry is already using a first stage reusable LV capability, which is currently being provided by the SpaceX[99] with its *Falcon 9* rocket. Blue Origin[100] is another private company that shows promise on this front. It has already demonstrated vertical landing of its sub-orbital *New Shepard* rocket on November 23, 2015 and is currently developing the orbital *New Glenn* rocket where the first stage is proposed to be reusable, similar to the *New Shepard* suborbital launch vehicle that preceded it[101]. SpaceX in particular has been leading the way in partially reusable launch capability as the company continues to carry out first stage landings on every orbital launch when allowed by the mission's fuel margin requirements and have demonstrated the reuse of a previously recovered first stage on March 30, 2017 for SES-10 mission[102]. Clearly, partial reusability capability can be considered now as an off-the-shelf technology. Extrapolating on this trend, a future variant is assumed which is referred to as a *Falcon 9 type* LV with both stages recoverable. Next, three primary categories of vertical launch LVs are defined based on the reusability capability as seen in the Figure 5.1. The figure shows multiple options of LVs decomposed into constituent launch elements in each category. In order to address the entire spectrum of reusability aspect of the LVs, three LV case-studies are selected for this research from each category. They are described as follows;

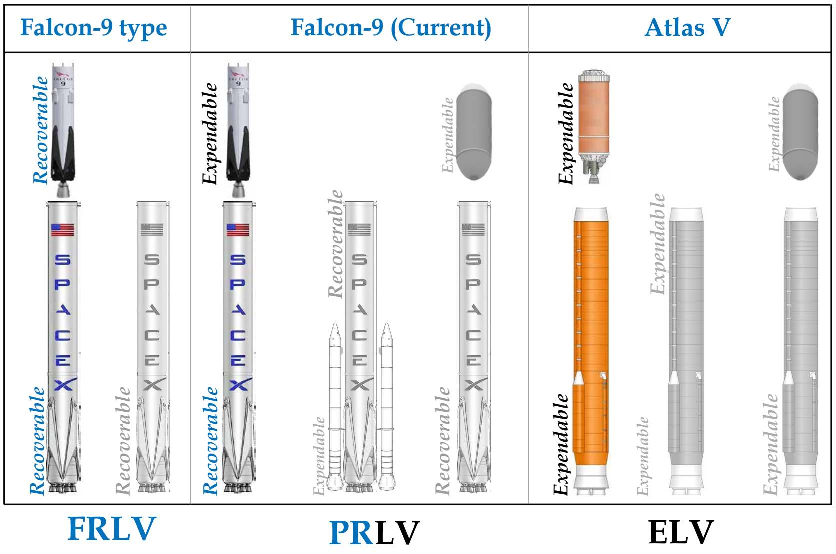


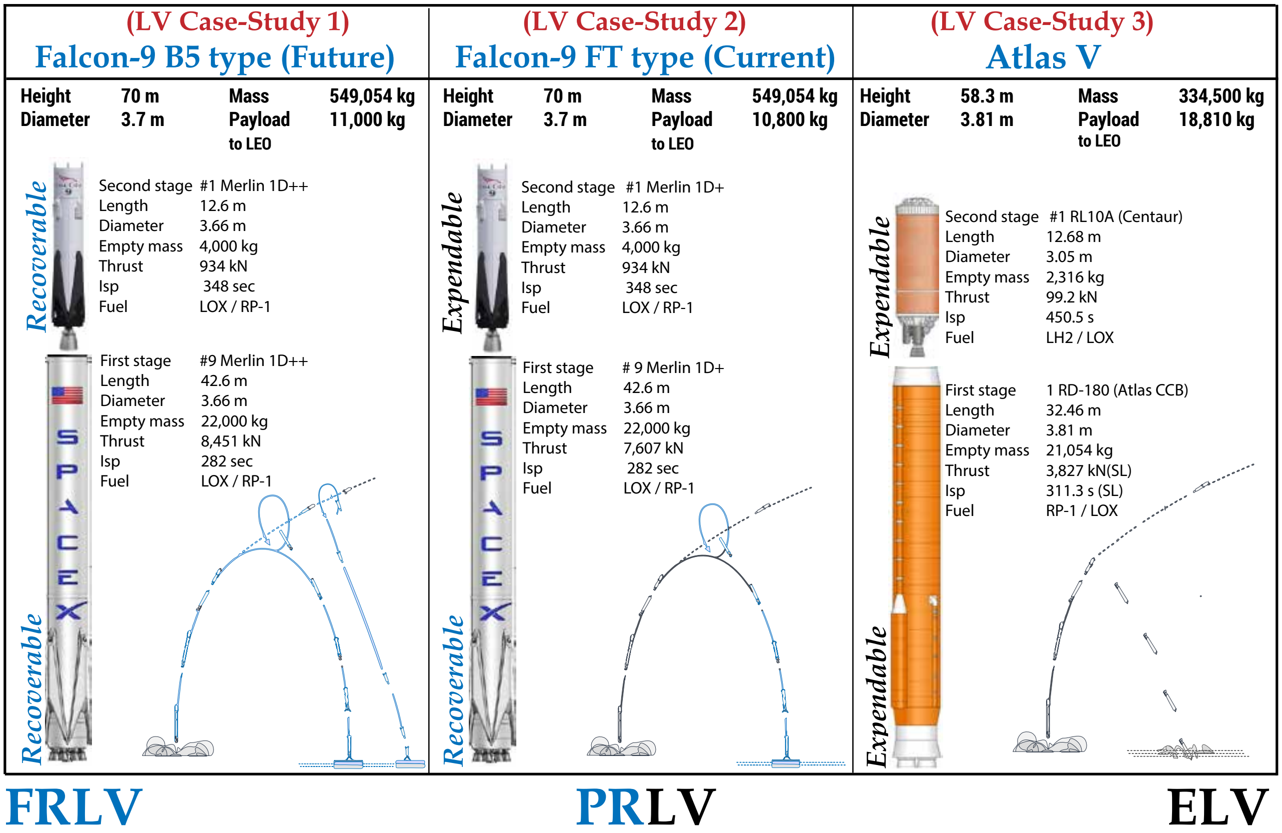
FIGURE 5.1 – Multiple sets of LVs could be seen for each category composed of various constituting elements. One representative case-study is selected from each category.

1. *Expendable Launch Vehicle (ELV):* Most common and prevalent category. Case-Study Selected - **ULA Atlas-V**.

2. *Partially Reusable Launch Vehicle (PRLV):* Currently operational and in-development vehicles that can recover atleast first stage of a multistage LV. Case-Study Selected - **SpaceX Falcon 9 FT version**.

3. *Fully Reusable Launch Vehicle (FRLV):* An extrapolation of the current PRLVs based on the assumption of a recoverable second stage. The first stage is assumed same as the Falcon 9 while the second stage is an advanced reusable version of current second stage of the Falcon 9 launch vehicle. *Falcon 9 Block 5* is the next version of the Falcon 9 launch vehicle which is currently under production and serves as a model, Case-study Selected - **A future Falcon 9-type LV with both stages reusable.**

The selected case-studies are representative vehicles from each class and are used in this research in the execution of SAS-GDSP at hierarchy level-1, the VTHL system. Figure 5.2 provides the overview description of each case-study selected. Note that the assumed future Falcon 9 vehicle has a lower LEO payload capacity since some fraction of the fuel is reserved for vertically landing the stage similar to what is being done currently with the first stage.



* Case-1 Performance and Physical characteristic values are approximated values based on the current Falcon 9 Full Thrust version.
** Vaccuum Isp values are used for the Second Stage and Sea-Level values for the First Stage.

FIGURE 5.2 – Representative vehicles and their characteristic physical and performance values as selected from each category as the representative case-studies.

## 5.2 *SAS-GDSP Methodology for Hierarchy Level-1: VTHL*

The SAS-GDSP solution is generically applying the four steps, namely; 1) Mission Analysis, 2) Technology Requirements, 3) Hardware Selection and 4) Cost-per-Performance Solution screening. These four steps are applicable to the VTHL configuration where the entire VTHL is considered as one system. These steps are explained here for the Hierarchy Level-1 application.

### 5.2.1 Mission Analysis

The *Mission Analysis* step acts as the fundamental guide to distinctly identify the primary performance parameters and the corresponding primary design variables that affect the performance requirements. With this step, the designer gains a physical understanding of the system through a parametric model. The goal is yet not to solve the equation since at this stage not enough information is available about the system. Instead the focus is to derive the fundamental parametric relationships that explore the sensitivity of the gross or highest-of-importance design drivers.

The *Mission Analysis* step has been executed for the LRV application in Section 4.3.1 where an elaborate system of equations has been providing guidance. The complete VTHL system is composed of both, the vertical takeoff and the horizontal landing phases. The system of equations developed for the reentry mission profile in the previous chapter is included here by definition. The vertical takeoff phase is addressed next.

Dergarabedian and Dyke[83] provide a simplified first order estimate for launch vehicle mission performance analysis which is used here. The mission profile considered is made up of a simplified set of equations that characterize an expandable ballistic launch vehicle.[2].

Primary performance measures of a multistage ballistic launch vehicle mission profile are derived from the rocket equation.

$$V_i = I_i \, g \, ln(r_i) \tag{5.1}$$

where,

$I_i$ : stage i specific impulse; thrust divided by flow rate of fuel;

g : gravitational constant

$r_i$ : stage i burnout mass ratio; initial mass divided by burnout mass;

$V_i$ : velocity added during stage i;

Following section now provides equations for the burnout velocity, burnout altitude, burnout surface range and the total range of the laucnh vehicle mission.

» *Stage Burnout Velocity:* Burnout velocity for a stage is depending on trajectory parameters like stage burnout time ($t_b$) and burnout velocity angle ($\beta_b$) related by following set of equations;

$$V_b = V^* - V_L \tag{5.2}$$

where term $V_L$ is the total velocity losses, is calculated as sum of gravity loss ($V_g$) , drag loss ($V_d$) and the nozzle-pressure loss ($V_a$). These are calculated by simplified equations provided by Dergarabedian and

[2] The mission profile for a reusable launch vehicle implies additional equations that are not discussed here since the LV options are not sized like the LRV options. When sizing the LV cases as done with the LRVs, the vertically landing phase must be considered as it implements further constraint on the LV subsystems.

Dyke[83] in terms of constant coefficients, as follows;

$$V_L = V_g + V_d + V_a \tag{5.3}$$

$$V_g = (g\, t_b - K_{gg}) \left(1 - K_g(1 - \frac{1}{r})\right) \left[\frac{\beta_b}{(90^o)}\right]^2 \tag{5.4}$$

$$V_d = K_d \frac{C_D\, S_{ref}}{W_o} \tag{5.5}$$

$$V_a = K_a \tag{5.6}$$

where, terms $K_{gg}$, $K_g$, $K_d$ and $K_a$ are constant coefficients which are provided as functions of vehicle parameters like $I_{sp}$, $C_D$ and take-off thrust to weight ratio ($\frac{T_o}{W_o}$) in several graphs.

» *Stage Burnout Altitude:* Burnout altitude is another important parameter that defines the payload capacity of the launch vehicle. A closed-form expression is used here to calculate the distance traversed by an ideal rocket in vertical flight (constant g, no drag, constant specific impulse) and then finding burnout altitude by including flight losses similar to burnout velocity case. Following equations are used

» *Burnout Surface Range:* Then, burnout surface range and total range of the vehicle are found by equations

$$x_b = 1.1\, h^* \, \frac{\beta_b}{(90^o)} \tag{5.7}$$

$$R = D\, (e^{\frac{V^*}{B\, g}} - 1) \tag{5.8}$$

where terms D and B are constant coefficients as well.

With the above set of parametric equations, it is seen that the primary vehicle performance drivers are the propellant Isp, mass ratio (r) and take-off thrust to weight ratio ($\frac{T_o}{W_o}$). Rest other parameters can be derived in terms of these parameters. These parameters will thus be considered while evaluating the cost-per-performance of the VTHL system.

### 5.2.2 *Technology Requirements*

The *Technology Requirement* step of the generic SAS-GDSP is aimed at identifying the essential technology elements at the subsystem level. At this point in the process, the essential subsystems that are required for a full system integration have been identified through the Mission Analysis step. For the VTHL system, the subsystem level is the SAV level that includes the LRV and LV options. Thus, the technology requirements for the VTHL system are implied on its constituting components, the LRVs and LVs.

The LRVs have been sized in the previous chapter and a design solution space for all of the converged vehicles has been obtained. The LV options are considered here in the form of the three case-studies selected in Section 5.1.1[3]. In this context, the required technology for the subsystem is already selected at this step but have not yet been integrated together.

This is done with the next step.

### 5.2.3 *Hardware Selection*

Hardware selection is essentially the matching of subsystem components to define the physical feasibility of the overall system and to develop a solution space of feasible design options. For the VTHL system, the subsystem elements are the LRV and LV options. The LRVs have been sized in the previous chapter and the overall solution space of the lifting body LRVs is used here. The three LV case-studies are representative of the second subsystem element and the selection of LV options.

The next step is to find feasible combinations of both these element options that represent the design solution space for the overall VTHL system. It must be noted that the total number of the lifting body LRV designs obtained in Chpater 4 was 636 and the number of LV options is 3. Thus, a total of 1908 VTHL combinations are possible. Of course, not all the options are going to result in a feasible design. In order to find the feasible VTHL design solution space, the pre-selected LV cases are used to implement a selection criteria for the sized 636 lifting body LRVs. The primary selection criteria used for this purpose are discussed next where each criteria acts as a filter to select the LRV design solutions that can fit with the LV options. The first two criteria are necessary requirements while the third criteria is optional. These are described as follows:

- Overall LEO capacity of the LVs : This implies the weight carrying limit for each LV case. The lifting body LRV design solution space is first filtered for this criteria in each LV case.
- The geometry constraint of the LVs : The base diameter of the lifting body LRVs is selected as the imposing constraint. The LRV design options that pass the first criteria are then screened for this second criteria. The diameter of the LVs cross-section is the limiting constraint and the LRV design options that exceed the LV cross-sectional diameter are rejected at this step.
- Overall fairing volume capacity of the LVs: This criteria assumes the constraint that the lifting body LRV must be able to fit inside

[3] In an ideal case scenario, the LVs would be sized similar to the LRVs using the same template as implemented for the LRV cases. This step is skipped here to confine the scope of the research. The application of the SAS-GDSP for the LRV cases validate its application at the SAV level and thus is applicable to the LV segment of the SAVs.

the fairing of the LV. Once the total weight and the LV cross-section are imposed, the fairing volume constraint further reduces the total number of feasible LRV design solutions which can be integrated with the selected LRV designs.

After the application of the above defined criteria, the total number of possible VTHL design solutions is obtained. This is theoretically same as the sizing step of the previous chapter where the subsystems are integrated in the MDA framework to generate the total number of the feasible design solutions.

### 5.2.4 *Cost-per-Performance Solution Screening*

The total cost analysis for the three LV case-studies is addressed here. The total cost of the VTHL system is calculated as sum of the total cost of the LRV and the LV segment. The total cost for the lifting body LRVs has already been calculated in the previous chapter. The following description addresses cost model for the LV segment.

#### *Total Life-Cycle cost Model for LV*

The overall cost estimate model of the LV element of the VTHL system is also taken from D. E. Koelle's *Transcost Model* and calculates the same three submodels as done for the LRVs, namely; 1) the Development Cost[4], 2) the Production Cost, and 3) the Operations Cost.

Values of cost factors used for LV cost estimates:

- $f_0 = 1.04$
- $f_1 = 1.1$
- $f_2 = 1$
- $f_3 = 1.3$
- $f_4 = 0.58$
- $f_6 = 1.3$
- $f_7 = 1.2$
- $f_8 = 1$
- $f_9 = 1.08$
- $f_{10} = 0.8$
- $f_{11} = 0.5$

$$\text{Total Cost}_{LV} = \text{Total Dev.Cost}_{LV} + \text{Total Prod.Cost}_{LV} + \text{Ops.Cost}_{LV} \tag{5.9}$$

Koelle provides cost estimating relationships (CERs) for expendable and resuable LVs which are used for corresponding elements. Following next are the CERs for each submodel as applied for individual LV cases.

» *Development costs* The total development cost is estimated only for the first case which is an assumed future, fully reusable capability. Following equations are used for the Vehicle Development Cost (VB) and the Engine Development Cost (EL):

$$\text{Total development cost} = f_0 \left(H_{EL} + H_{VW}\right) f_6 \, f_7 \, f_8 \tag{5.10}$$

where,

$$H_{EL} = 277\, M^{0.48}\, f_1\, f_2\, f_3\, f_8 H_{VB} = 803.5\, M^{0.385}\, f_1\, f_2\, f_3\, f_8\, f_{10}\, f_{11} \tag{5.11}$$

» *Production costs* The total production cost for the LRV is calculated for the liquid rocket engines (EP) and the LV stage vehicle. It is given

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[4] This submodel is only executed for the first LV case which is the system that is assumed to be fully reusable. The other cases are already developed vehicles and their development cost is not calculated.

by the following equation:

$$\text{Total Production cost} = f_0^N \left( \sum_1^n F_{VP} + \quad \sum_1^n F_{EP} \right) f_9 \tag{5.12}$$

where $N$ is the number of stages or system elements, $n$ is the number of identical units per element. Production cost estimates for Liq. Rocket Production Cost $F_{ET}$, and the LV Stage Production Cost $F_{VP}$, are calculated as follows;

$$F_{EP} = 1.2\, M^{0.535}\, f_4\, f_8\, f_{11} \tag{5.13}$$

$$F_{VP} = 1.84\, M^{0.59}\, f_4\, f_8\, f_{10}\, f_{11} \tag{5.14}$$

» *Operations Cost* Koelle defines Direct Operations Cost as composed of following elements,

- Ground Operations
- Materials & Propellants
- Flight Operations
- Transport & Recovery
- Fees & Insurance

Of these elements, only the Ground Cost and the Flight Operations cost are included to calculate the Operations Cost for the LRVs. Following set of CERs are given by Koelle for these elements;

$$\text{DOC} = C_{OPS} + C_M \tag{5.15}$$

where, the Ground Operations cost, $C_{OPS}$ and the Flight Operations Cost, $C_M$ are given by following set of equations;

$$C_{OPS} = 12.24\, {M_0}^{0.67}\, L^{-0.9}\, f_4\, f_8\, f_{11} \tag{5.16}$$

$$C_M = 60\, L^{-0.65}\, f_4\, f_8 \tag{5.17}$$

$M_0$ is the TOGW at the takeoff and L is the launch rate, L = 25 flights per year assumed flight rate here.

## Total Cost Estimate and Performance Measure of the VTHL System

Once the total cost of the LV cases are calculated, the total cost of the complete VTHL system can be then estimated as; $\text{Total Cost}_{VTHL} = \text{Total Cost}_{LV} + \text{Total Cost}_{LRV}$ where, $\text{Total Cost}_{LRV}$ has been calculated in the previous chapter. The total cost estimate for the entire system is a unit of relative measurement, which is used for comparing various VTHL system options.

The final step now is to calculate the overall performance of the VTHL system options. For the LRV case-studies, three performance indices were defined, namely; $1)Perf_{Eff}, 2)Vol_{Eff}, and 3)I_{Str}$. These parameters are representative of the how efficiently does the LRV perform, how efficiently does the LRV incorporate total volume and how efficiently does the LRV incorporate total weight, respectively. A similar measure of overall performance for the VTHL system can now be defined by including a performance factor representative for the LV along with the LRV performance indices.
The *Mission Analysis* step for the LV identified the significant primary design drivers. Of these, the two non-dimensional parameters, thrust-to-weight ratio ($T_o/W_o$) and the mass-ratio ($m_o/m_b$) of the LV are selected and multiplied with the $Perf_{Eff}$ factor of the LRV stage to define an overall performance index of the VTHL system. The selection of these LV parameters is based on their non-dimensional form that can be easily accommodated with the non-dimensional LRV performance efficiency factor. Thus, the overall performance index for the VTHL system is defined as follows;

$$(I_{Perf})_{VTHL} = LRV_{Perf} \left( \frac{T_o}{W_o} r \right)_{LV} \tag{5.18}$$

With the performance index and total cost calculated for the VTHL system, the overall design solution space for the VTHL solutions can be assessed which allows the selection for the most optimal design concept. The next section discusses the results obtained for the VTHL design solutions.

## 5.3 *Results*

Each LV case has been matched with the LRV options that met with the LV constraint limits, thus resulting into a feasible VTHL system solution space. The cost and performance analysis conducted assess the VTHL options for each LV case. The final results are interpreted for the overall VTHL system and thus are affected by the design sensitivities of the LRV options as well. This aspect must be considered at all times since the comparisons are conducted for each *LV based* VTHL systems and might mislead to the interpretation as solely based on the LV. Total of 1172 VTHL design concepts are addressed next for each LV based VTHL configuration.

### 5.3.1 *LV-based VTHL systems comparison*

Figure 5.4 shows the first solution space for the VTHL cases that utilized a current Falcon 9 type Partially Reusable Launch Vehicle (PRLV).

Total 344 VTHL system design solutions have been identified in this solution space[5]. As seen in the figure, the boxed region identify as the region of the most optimum design points which show maximum system performance, minimum system cost and minimum total weight.

Next, the results for the VTHL systems employing a future Falcon 9 type[6] Fully Reusable Launch Vehicle (FLRV) case are shown in Figure5.5. A total of 369 VTHL design solutions are addressed in this solution space and the region of most optimum design solutions is identified along with comparisons with the PRLV based VTHL. As seen in the figure, the overall cost of this case is higher than the PRLV based VTHL solutions. This is partly due to the fact that the cost model calculated LV development cost for only this LV case (since this capability is yet not available). Additionally the overall performance is also seen as slightly lesser than that of the PRLV-based VTHL solutions. This factor again is influenced by the LRV options along with the LV type. Also, the overall weight of this case is considered same as that of the PRLV LV and this might be cause the overall performance of the VTHL systems to be dropped. Additionally, the LRV options for this case are not necessarily the same ones as that with the PRLV case. This limitation of the synthesis system is still being addressed and is such due to the complex data structure arrangement of the synthesis system. The data is extracted in several layers, first for the single point LRV convergence, then for the multi-point design solution space, followed by the cost and performance analysis on the solution space and matching with the LV constraints and finally merged with the cost and performance of the LV options for the overall VTHL results.

Finally, the last batch of results are addressed for the Atlas V type fully Expandable Lauch Vehicle (ELV) based VTHL systems. Figure 5.6 visualize the overall solution space for the ELV-based VTHL systems that contains 459 design points. This is primarily due to higher LEO payload capacity of the Atlas V LV. The region of optimum design points has most design solution points for this case. Additionally, it must be noted that the ELV based VTHL solutions have the maximum total VTHL cost among all three LV based VTHL systems and show minimum overall VTHL performance. On an average, the ELV based VTHL show around 50 percent reduction in the overall system performance while cost 300 percent more than the other two VTHL types. This trend clearly highlights the advantage of employing a reusable LV for any type of LRV configuration.

### 5.3.2 *Summary*

The SAS-GDSP solution has been applied for the VTHL SAS category in this chapter. The VTHL systems design solution spaces has been

[5] This means that 344 LRV options met with the Falcon 9 payload weight and fairing diameter constraint.

[6] Based on assumed values for Falcon 9 Block 5 type LV.

generated that contain 1172 VTHL solution concepts. The results are discussed based on the LV type used in the VTHL system but compare the overall SAS performance and cost estimates. This implementation validates the generic capability of the SAS-GDSP at the top-most hierarchy level. This capability is a prototype synthesis process which increases the CD assessment scope vertically across system hierarchy levels and provide the decision maker with valuable insights on systems and subsystems level. The results compare a large number of design options and hence, certain anomalies are seen which are being addressed currently.

The primary contribution from this chapter is the demonstration of a truly state-of-the-art multidisciplinary capability. The solution space provides a powerful tool that lets the decision maker scan across multiple design options.

It must be noted here that the disciplinary methods applied within the LRV case-studies are bound by the VTHL range of technology-mission-operations domains and are only applicable to this specific class of SAS. The SAS-GDSP solution process however is a unique CD methodology that is generic in nature and is applicable to all other SAS categories if the appropriate disciplinary methods and mission profile analysis is applied.

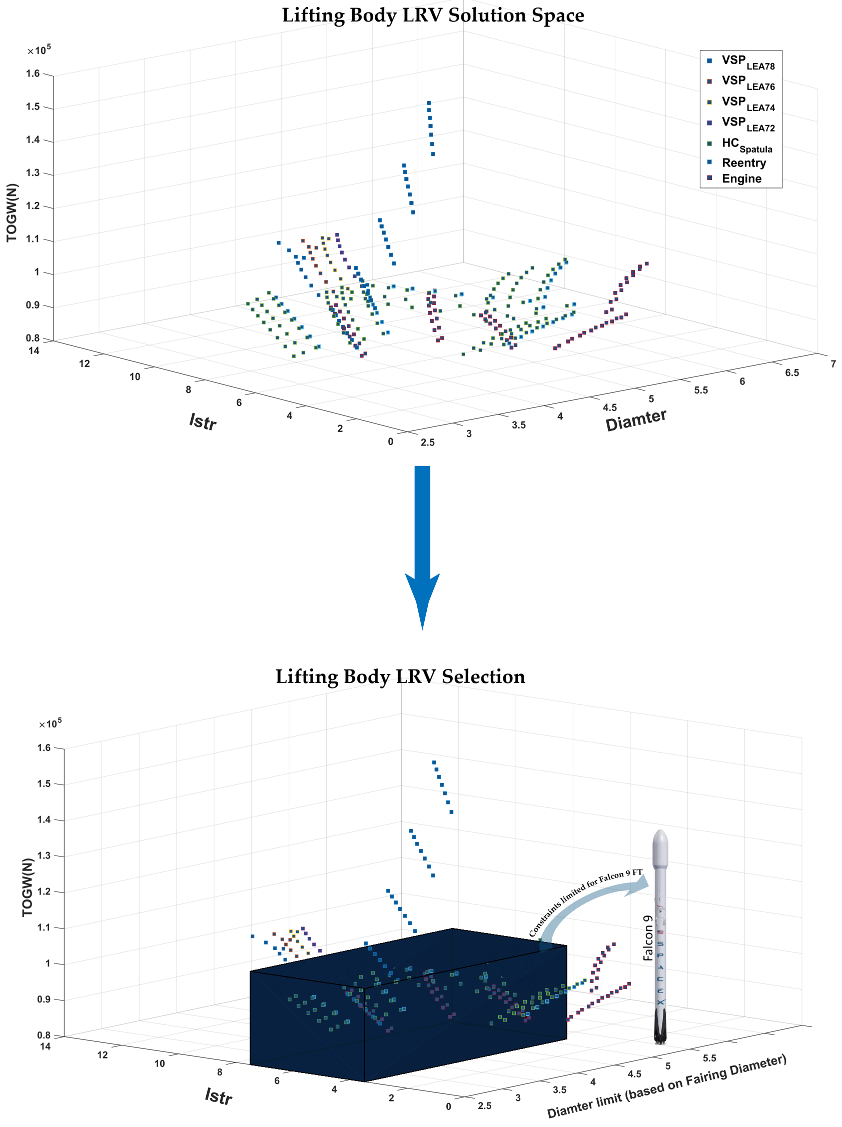

FIGURE 5.3 – The LRV design solution space generated in the previous chapter is now screened for constraints implied by the LV selected. Falcon 9 case is shown by the block that contains all the LRV options that can be integrated with the Falcon 9 vehicle. The necessary requirements to fit the LV have been implemented by first two criteria.

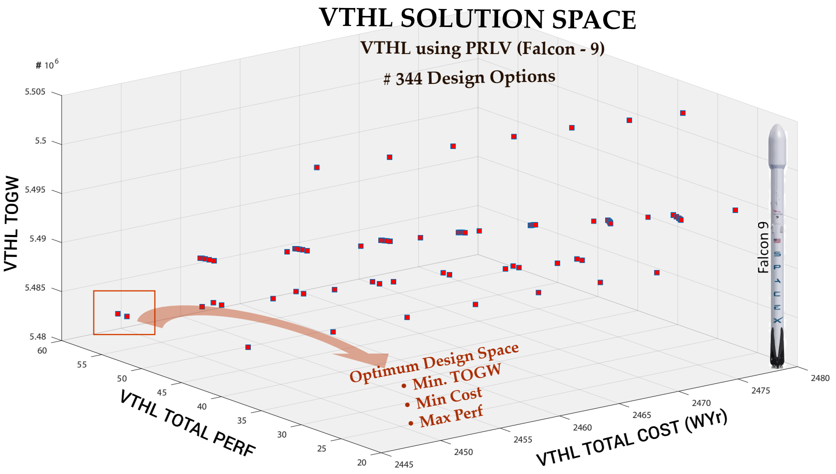

FIGURE 5.4 – PRLV Based VTHL Solution space compares all VTHL options that use Falcon 9 LV and Lifting Body LRVs. Note that the total number of design points in the boxed region overlap due to a high density of design points in the limited solution space. The total number of design points in the optimum region are more than two, as it might appear.

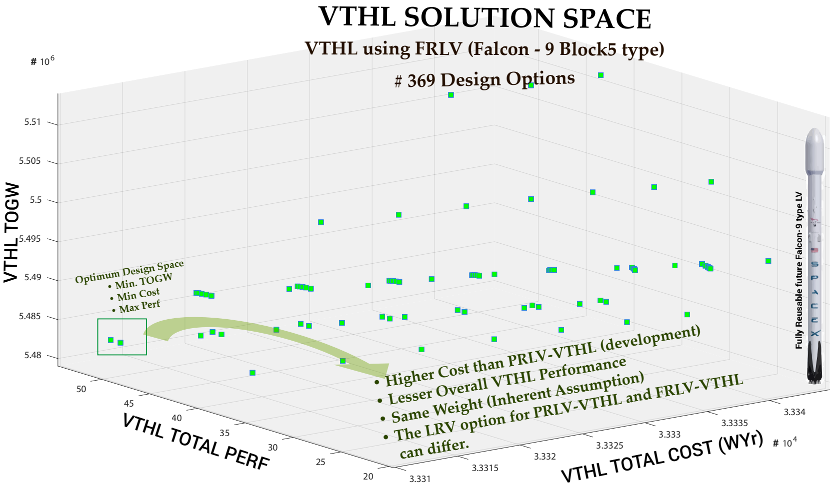

FIGURE 5.5 – The overall results are in comparison with the PRLV based VTHL systems. Similar to the PRLV based VTHL solution space, the optimum design solution region here also contains multiple design solutions and must not be misjudged by the visual limitation of the high density solution space.

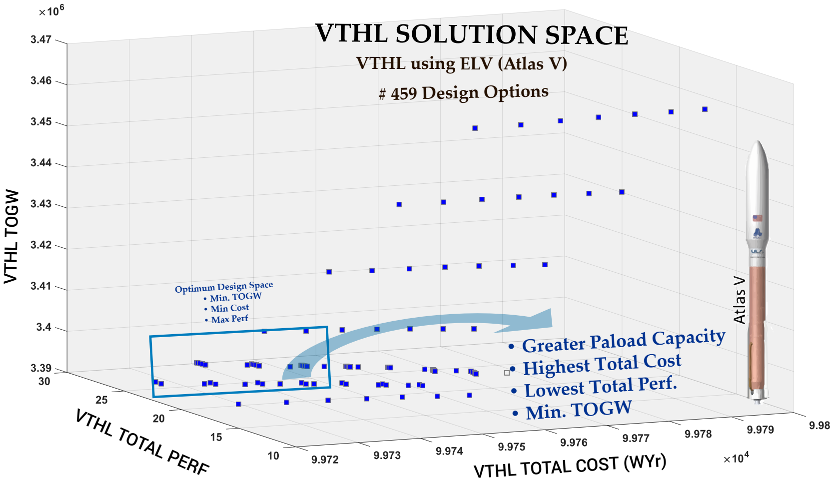

FIGURE 5.6 – The overall results show the drastic reduction in overall VTHL performance at a significant increase in the total systems cost.

*Chapter 6*

# ORIGINAL CONTRIBUTIONS

This dissertation produced several significant original contributions to the field of aerospace and the multi-disciplinary sciences. They are addressed as follows;

## Original Contributions in Ideology

» The Generic Design Synthesis Process for the Space Access Systems (SAS-GDSP)[1] is a novel approach that contributes to the ideology of the multi-disciplinary sciences, flight vehicle synthesis and the conceptual design assessment practices. The proposed solution process expands the scope of the conceptual design synthesis practices vertically and horizontally. The vertical expansion refers to the capability of the solution process in assessment of the SAS at Hierarchy Level-1 as a generic system. The horizontal expansion is the inclusion of the Mission Analysis and the Cost-per-Performance Solution Screening steps in the conceptual design practices, beyond the technology-hardware integration.

» The SAS-GDSP is a generic process which shows its application at the Hierarchy Level-1 for the SAS and at the Hierarchy Level-2 for the SAV. This dissertation also serves as a template for implementing the SAS-GDSP solution for the other SAS categories. The three Systems Modules and four System Design Processes are generic in nature and can be implemented for any SAS or SAV category.

» The AHP quantitative model[2] produced for the assessment of the LRV projects is a novel and generic approach to effectively capture top-level knowledge from the legacy programs.

## Original Contributions in Data, Methods and Sizing Implementation

» The literature review for the VTHL systems[3] resulted in creation of an expansive and organized central library containing more than 600 literature sources. The library is classified with the standard defined keywords that makes it easily accessible and practically usable for sharing with the research community. Extensive database and knowledge base have been created from this library.

[1] See Chapter 3

[2] See Chapter 2

[3] See Chapter 2

- The dissertation produced the most comprehensive account for the LRV cases. The AHP model uses information from more than 172 literature sources and provides a quantified summary that can be of guidance to the discipline specific researchers. The 60 LRV programs were assessed for primary disciplinary knowledge contribution. This process was greatly benefited with the valuable data and knowledge bases of the AVD laboratory that provided a treasure trove of exotic aerospace literature to the author. In return, the author feels equally satisfied to be able to advance this exotic data rich capability even further.

- The execution of the SAS-GDSP has been verified for hierarchy level-1[4] and hierarchy level-2[5] . This extensive process required development of new discipline analysis methods for primary design disciplines. The research has been significantly benefited from the existing AVD-DBMS platform. The DBMS provides a state-of-the-art modular synthesis capability that enabled the author to take the research to an exceptional level of creating mammoth amount of data and information. The synthesis activity resulted in sizing more than 700[6] LRV design concepts. This first level of LRV sizing enabled to compare more than 1100 distinct VTHL options across the board consistently. It must be mentioned here that the results presented in this dissertation represent less than half of the total sizing executions implemented as the first seventy percent of the design studies were a big learning curve that the author had to go through. The primary design folder shows a total memory storage of 106 GBs of data content and still show a lot of scope to further explore new design solution spaces and develop new trends.

[4] See Chapter 5

[5] See Chapter 4

[6] This includes total number of design points converged for the X-20 and LB cases

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# *Appendix A*

# LRV AHP SCORES JUSTIFICATION

## *A.1 US LRV Case-Studies Assessment: Tsien SpacePlane - SNC Dream Chaser*

The AHP model developed for the assessment of the LRV case-studies is applied to assess the LRV programs initiated in the United States of America, beginning with the 1949 Tsien's spaceplane concept, to the current day SNC Dream Chaser. A brief overview of every case-study is provided along with the AHP scores to identify the major contributions, and rationalize the disciplinary criteria scores assigned to every case-study. An evolution pattern is observed while assembling the LRV data-base as many case-studies are connected together, either under a common program structure, or through development and application of technology from one program to other. This commonality and connection is discussed with the results to chart the LRV design and technology evolution. Readers are advised to consult the common legend given in Figure A.1, while reading the AHP result's and LRV evolution's visualization .

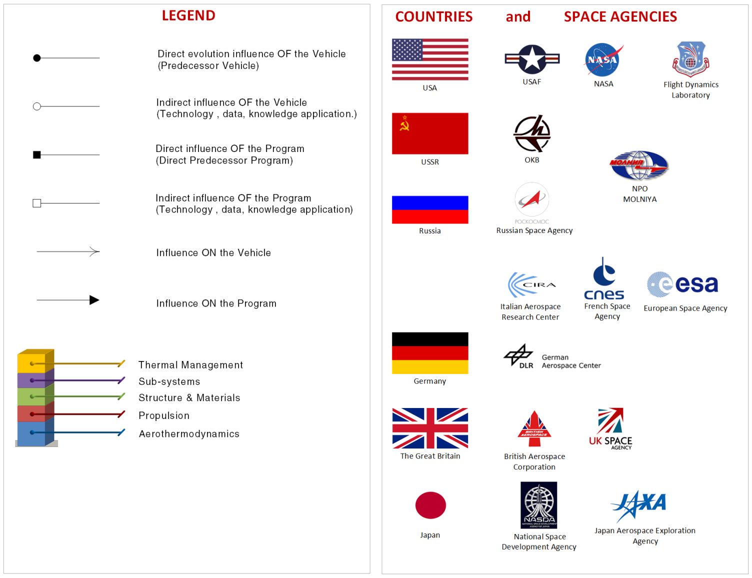


FIGURE A.1 – Legend for reading the AHP model scores and LRV evolution plots

### *A.1.1 1950s: The X-20 Family*

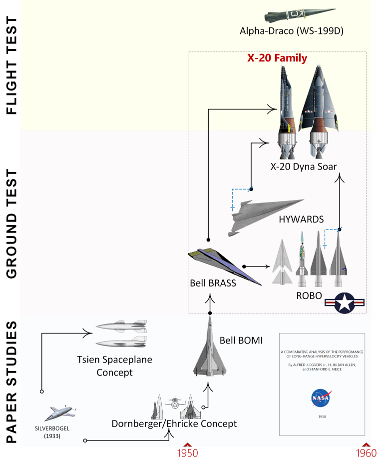


FIGURE A.2 – 1950s: LRV Evolution

Beginning of the US based LRV programs can be traced back to the period following operation Paperclip when, *"Germans, primarily scientists but also engineers and technicians, were brought to the United States from Nazi Germany."[103]* Sänger's Silvervogel design was brought to the US as part of operation paperclip, when Hsue-shen Tsien, a USAF colonel at the time, was "sent by the Army to Germany to investigate the progress of wartime aerodynamics research. Qian investigated research facilities and interviewed German scientists including Wernher von Braun and Rudolph Hermann"[104].

Later, while working at Califormnia Institute of Technology in 1949, Tsien conceptualized a hypersonic research vehicle to be developed into a transcontinental rocket-liner[32]. Although the concept was not feasible with the technology available at the time [38], it is one of the first few proposals to document a lifting reentry concept applied to space access system. Contemporary with Tsien; Ehricke and Dornberger developed several LRV concepts in early 1952 while working at Bell Aircraft[28]. These designs became the basis of the Bell BOMI concept, one of the first LRV projects undertaken by a major aerospace manufacturer of the time. BOMI was selected by the USAF in 1954 for the detailed design analysis, to investigate design and development problems associated with hypersonic flight regime[105]. Under the USAF designation MX-2276, BOMI addressed detailed technical assessment of vehicle's aerodynamics, structure, propulsion and trajectory analysis, providing valuable guidelines for an operational LRV[106]. Lessons learned during BOMI design development led the USAF to assign Bell with further investigation of a manned, hypersonic glide weapon system, under project BRASS in 1956. Bell improved on the BOMI design through wind tunnel tests and other experimental testing in propulsion, structures, aerothermodynamics and thermal management disciplines[107]. BRASS incorporated these changes, and further tested and developed several state-of-art technologies in these four disciplines, with major emphasis on thermal active cooling techniques and effect of various propellant combinations [40]. Around the same time, the USAF initiated studies to develop a piloted hypersonic Rocket Bomber(ROBO) and received proposals from Conviar, Douglas, Lockheed, NorthAmerican, Bell and Martin. Bell led the project, with experience gained during the research and experiments conducted for BRASS, which was also the basis of Bell's proposal for the ROBO[38]. While ROBO and BRASS were targeted towards developing an operational hypersonic weapon system, it was realized that operational environment beyond 100 nmi was essentially unknown. and needs to be understood before an operational vehicle could be developed. The USAF initiated project HYWARDS in 1956 for this purpose, with two very different vehicle concepts from NASA Langley(headed by Becker) and NASA Ames(headed by Allen and Eggers)[108]. HYWARDS studies contributed significantly towards understanding the aerodynamics and thermal characteristics of the hypersonic vehicle design. Hallion's quote further highlights HYWARDS' contribution:

> *"This was the first clear delineation of the possibility of aerodynamic design features which could significantly alleviate the heating and ease the hotâĂŤstructures problems. Later application of these principles to actual flight systems was first made in the X-20 and they are also obviously applied in the current Space Shuttle."[32]*

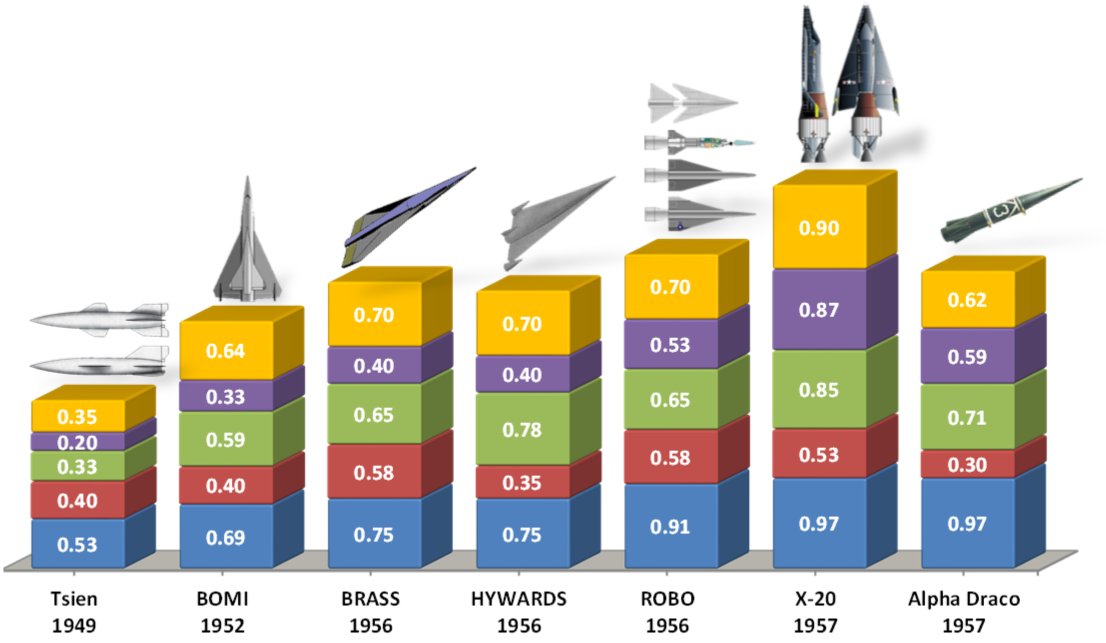


FIGURE A.3 – 1950s: AHP Results

In 1957, the USAF decided to consolidate the details of BRASS, HYWARDS and ROBO programs into three steps of one single program under official designation X-20, later known as DynaSoar shortened for Dynamic-Soaring[75]. This was one of the biggest venture undertaken by the USAF to develop a LRV. The X-20 program produced critical research breakthroughs that influenced future generations of LRV designs and technology. The program was cancelled in 1963, just two months before the manufacturing phase began and the effort had already reached a budget of $410 million[40]. X-20 has been studied and documented extensively by several historians and engineers alike as it is one of the 'what-if' programs that showed tremendous potential. Geiger, [30, 75, 109] Houchins [97] and Godwin[31] have addressed X-

20 program in great detail, thereby providing valuable contributions of the program that was utilized in LRV programs of the 1960s which directly influenced the development of the Space Shuttle. These accounts, along with several other historiography literature, mention the X-20 as a major milestone in the history of hypersonic research development. Rose remarks this as following:

> *"Dyna-Soar was certainly a very advanced piece of engineering, with many systems and innovations that would find their way into future aircraft and spacecraft."*

Independent and contemporary of the X-20 program was McDonnell's Alpha-Draco, developed for the USAF as a part of the WS-199 project. It was a research vehicle to explore the feasibility of the boost-glide mission. Officially designated as WS-199D, Alpha-Draco yielded important data on the aerodynamics of hypersonic flight. Hallion describes the importance of Alph-Draco in following quotes:

> *" Alpha Draco was a little-known but significant step on the road to understanding the aerodynamic, heating, and maneuvering challenges of hypersonic flight." It anticipated later programs to acquire a data base on hypersonic reentry conditions, vehicle behavior, and flow characteristics (particularly boundary layer transition from laminar to turbulent flow, and its impact upon heating rates)."[35]*

The main highlight of the 1950s was the X-20 program for LRV design, which combined all previous efforts into one program. The final years of the decade witnessed a large number of ground tests and research activities undertaken towards understanding the hypersonic environment, and developing technology to meet the challenges imposed by the X-20 mission requirements. The AHP results for this decade are shown in Figure A.3

### *A.1.2 1960s: The Lifting Bodies*

Momentum gained with the X-20 program during the late 1950s was carried on in the early 1960s. While the X-20 evolved from Sänger's Silvervogel concept employing a delta-wing configuration, the lifting body design emerged from the feasibility and performance studies by Allen, Eggers and Neice[20]. Although the lifting body configuration was examined by the USAF in the late 1950s under some preliminary studies, the real development of this design began during the early 1960s, which was also a declining phase for the X-20 program. Hallion comments on this transition of interest as follows:

> *"In June 1962, X-20A faced sniping criticism from partisans within the USAF Space Systems Division (SSD) favoring development of a rival–a small piloted lifting body for satellite inspection and space logistics known as SAINT II. Though Dyna-Soar weathered this storm while SAINT II itself succumbed, it was clear that Dyna-Soar was losing its appeal."*[32]

Further discussion of LRV programs of the 1960s is addressing the families of vehicles developed in a common program.

**The RTTOCV Family** NASA funded studies in 1962 for a "Reusable Ten Ton Orbital Carrier Vehicle" (RTTOCV), which represents a group of concepts by leading aerospace companies of the time. Several of these proposals were refined version of proposals submitted for ROBO and X-20 programs, while others like Douglas Astro were derived from the lifting body configurations developed by the NACA in the late 1950s. Heppenheimer describes some of the candidate concepts considered under RTTOCV study as follows:

> *"This study, called "Reusable Ten Ton Orbital Carrier Vehicle," awarded contracts of $428,000 to Lockheed and of $342,000 to NAA....Subsequent studies investigated additional alternatives and pursued design issues in greater depth. In 1965, General Dynamics defined a concept for a reusable second stage that had the shape of a lifting body...These studies concluded that, without exception, rocket engines were preferable to airbreathers for first-stage propulsion."*[110]

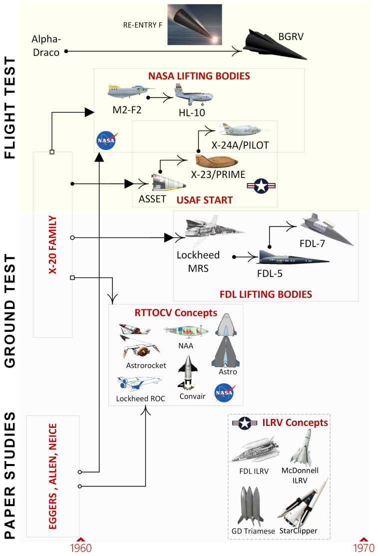
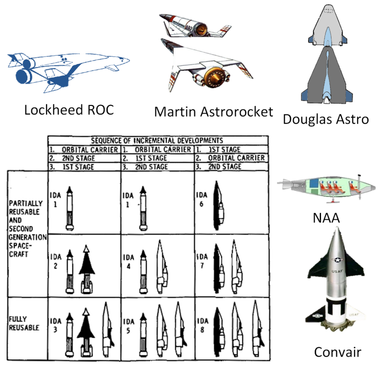


FIGURE A.4 – 1960s: LRV Evolution

Martin's Astrorocket[111] and Douglas' Astro[112] are notable proposals under RRTOCV family which show advanced understanding on systems feasibility and technology requirements for a fully reusable SAS. Reference [113] and [114] are NASA technical memorandum from 1967. They provide an overview of some of these concepts and lessons learned from a system feasibility point of view. Ultimately, they were influential while selecting vehicle configuration for the Space Shuttle[110]. Since no detailed technical reports could be located for any of these proposals in the public domain (most likely due to company proprietary reasons), this group is considered as one case-study in the AHP model. FigureA.5 visualizes some important concepts reviewed under this family.



Incremental Systems Development – NASA TM 53636

FIGURE A.5 – Concepts studied under RRTOCV program

## NASA Lifting Body Program

The NASA lifting body program began in 1962 with the M2 lifting body developed by Alfred J Eggers and associates at NASA Ames. Hoey describes this period as follows:

> *"From a NASA perspective, at least, the lifting body program had its beginnings in the studies of H. J. "Harvey" Allen, Alfred J. Eggers and others at the NACA Ames Aeronautical Laboratory in the early to mid-1950s into the blunt body reentry principle and the concept of lifting reentry from space. This predated Dyna-Soar. And it was these studies, plus roughly contemporary ones at the NACA Langley Aeronautical Laboratory on wingless lifting shapes, that led R. Dale Reed, a young engineer at the Flight Research Center, to advocate a flight research program involving lifting bodies."*[115]

What began as a wooden half-cone shell, quickly evolved to M2-F1 following a series of wind-tunnel tests by adding control surfaces, and further to rocket powered M2-F2 and M2-F3 following a series of modification augmented by the flight test data from M2-F1. The M2 lifting body program was complimented by NASA Langley's HL-10 in 1964, developed to test safe reentry landing techniques[116]. Both, M2 and HL-10 programs were significantly successful in demonstrating feasibility of lifting body configuration as a potential LRV and provided benchmark results in aerothermodynamics and subsystem disciplines for lifting bodies. The flight test data and lessons learned from these programs were critical in influencing many design features in the Space Shuttle[38, 40]. Hallion quotes:

> *"Clearly the M2 and HL-10 efforts constituted an important approach to hypersonic flight technology, even though they themselves never approached hypersonic velocities."*[33]

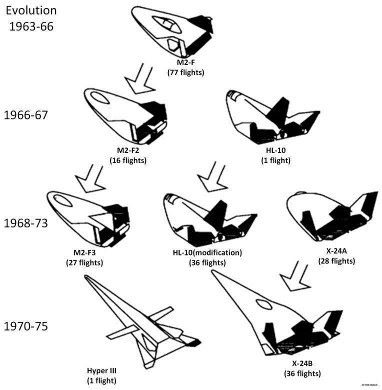


FIGURE A.6 – Vehicle configuration evolution under NASA lifting bodies[117]

While NASA Langley was still performing test flights for HL-10, another lifting body project, the X-24A was initiated at Edwards under the NASA-USAF collaboration in 1965. The USAF has been independently testing lifting bodies since the late 1950s, which evolved into the START program in the early 1960s. The X-24A was based on Martin SV-5P lifting body, which was originally designated as the PILOT under the USAF START program[115]. In this regards, X-24A/SV-5P/PILOT represents one of the first major joint venture between NASA and USAF. Major contributions of the X-24A were in the discipline of subsystems development by improving on the stability and control features of the lifting body design. Accomplishment of the X-24A are better expressed in the following quotes:

> *"Flight testing of the X-24A led to one significant accomplishment: the SV-5 shape was the only one evaluated in actual free-flight at hypersonic, supersonic, transonic, and subsonic velocities. Like the M2-F3 and HL-10, the X-24A demonstrated that shuttle-type hypersonic vehicles could make precise landings without power.."*[33]

The X-24B, the last vehicle in NASA's lifting body program was started in 1971 and had more in common with the flat-bottom FDL-7 than previous NASA lifting bodies(M2,HL-10 and X-24A). It is discussed in next sub-section with other LRV programs from 1970s.

With the X-24B, NASA concluded a very successful lifting body program as development of the Space Shuttle began in the early 1970s. The lifting body program contributed significantly to the Shuttle, with vehicle configuration selection in the early design phase and with stability and control during reentry, in the final design. Apart from the technical success, the lifting body program was also successful in using off-the-shelf technology for most parts, while developing a new configuration and improving on the vehicle design implementation rapidly. This could be an important lessons for those programs where high-demanding technology was the main cause of failure. It is no surprise that after four decades, the only LRV design currently under development, the SNC Dream Chaser, which is a direct decedent of HL-20 which had its roots in the lifting body program from 1960s. Figure A.6 shows vehicle evolution under NASA's lifting body program along with the number of test flights.

The START Program The START program was officially defined by the USAF following cancellation of the X-20 program in 1963. It was scheduled to test three lifting body vehicles namely; ASSET, PRIME and PILOT. Of these three, PILOT was merged with the NASA lifting body program as X-24A and is discussed earlier. ASSET and PRIME were precursor to PILOT and were solely under the USAF command with no direct involvement of NASA.

The ASSET lifting body[118] had its roots in the late 1950s when the USAF classified division, the Flight Dynamics Laboratory (FDL) at Wright-Patterson AFB, was given the responsibility for the aerodynamic, performance and aerothermodynamic tasks of the X-20[119]. The ASSET lifting body was essentially the forward 4 feet of the X-20 glider, developed with the primary goal of supporting the X-20 program in the disciplines of arothermodynamics and structures & materials development. Instead, by the time ASSET was ready for its first flight in September 1963, the X-20 was already in its final days and was eventually cancelled three months later[40]. ASSET carried on with extensive ground testing and eventually six test flights under the newly defined START program. Hallion's account of the ASSET and PRIME in "The Hypersonic Revolution - Vol.1"[32] is the most comprehensive description of these programs and provides valuable insights into the development process and important contributions. Following excerpts provide some overview of the significance of ASSET:

> *"ASSET had great application to future systems because it demonstrated the application of refractory materials on hypersonic vehicles; proved that the United States possessed a theoretical base and facility network capable of supporting the aerodynamic and thermodynamic design of such craft; and improved confidence in ground testing and theoretical predictive methods, particularly as involved preventing dynamic and aeroelastic problems on hypersonic vehicle designs....ASSET offered the first practical experience the aerospace community had with an actual lifting reentry vehicle returning from space at near-orbital velocities. Truly it was the pathfinder of lifting reentry...ASSET provided a wealth of data that contributed to the development of more advanced materials (primarily composites and carboncarbon) that would be available when Space Shuttle development began later in the decade."[32]*

ASSET was followed up by the PRIME, another lifting body configuration developed with a goal to explore the problems of maneuvering entry with emphasis on aerothermodynamics and subsystems discipline. Manufactured by Martin under official designation SV-5D and later referred as X-23, PRIME undertook several ground tests and three test flights that produced wealth of valuable data and technology. A complete list of PRIME's contribution to the hypersonic research body of knowledge is beyond the scope of the current paper. Hallion gives a detailed explanation of specific contributions in trajectory reconstruction, aerodynamics, heat shield and structure, guidance & control, flap actuation, environmental control, telemetry tracking & command, instrumentation and electrical subsystems categories. PRIME achieved all its initial objective with such a spectacular success rate that the development team cancelled two further planned launches and the project was concluded[38]. Rose comments on ASSET and PRIME is fitting to highlight the importance of these programs.

> *"It would be difficult to overestimate the importance of the ASSET and PRIME tests to the development of the Space Shuttle. "[38]*

**FDL Lifting Body Contribution** The contribution of the Flight Dynamics Laboratory or FDL in the field of hypersonic research is relatively unnoticed, given the important involvement of this organization in major hypersonic programs like X-20, Alpha Draco, NASA Lifting bodies, USAF START, the Space Shuttle, TAVs, BGRV and NASP. Reference [[119]] identifies the involvement of FDL in the hypersonic research development and comments*"...the Flight Dynamics Laboratory has been a major contributor to the understanding of hypersonic flow and pioneered the development of many innovative hypersonic vehicle concepts..."[119]* While supporting the X-20 program with the ASSET vehicle, FDL was influential in selection of the flat-bottom type shape, which differed significantly from the M2 round bottom body developed via the NASA lifting body program[40]. This difference in the geometry trend is seen to continue in parallel in both these programs until the X-24B emerges as a converging point, which utilizes X-24A sub-structure with the flat-botteomed FDL-7 outer mold-shape geometry[40]. Between 1964 and 1968, the USAF contracted Lockheed's Skunk Works to design a Mulitpurpose Re-usable Spacecraft(MRS). Lockheed's designs borrowed heavily from the X-20 and eventually evolved into the FDL-5, a flat bottom lifting body based on FDL's prior experience with similar geometry configurations[38].

The FDL-5 is the only vehicle from the FDL lifting body series which has been assessed by the AHP model in the present context, as it is theoretically one of the best performing lifting body design. The follow-on designs like FDL-7, FDL-8 and McDonnell's seminal model 176 are represented through the X-24B and X-24C respectively. The importance of the FDL-5 is emphasized via the following quote:

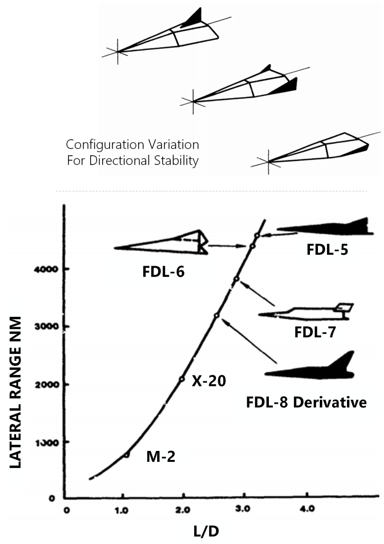


FIGURE A.7 – FDL-5 L/D comparison[119]

> *"The configurations chosen for more complete assessment were generally those with the higher aerodynamic performance efficiency as well as geometric com-*

> *patibility with the payload bay of the space shuttle. One of the more unique configurations developed was the FDL-5 series. The basic problem addressed in this design was to eliminate the fins of the vehicle without degrading the hypersonic L/D, the subsonic L/D and the hypersonic directional stability."[119]*

This effect is shown in Figure A.7.

The FDL-5 geometry and design philosophy proved to be a critical design point in the series of lifting body evaluation. It provided much critical insight regarding geometry configuration influences on vehicle's aerothermodynamic and stability performance. The FDL lifting body vehicles were highly classified and not much information is available in the public domain. Rose's remark on FDL-5 confirms the secrecy:

> *"Wind tunnel testing of models was undertaken and there have been claims that the mock-up seen in two photographs actually shows a prototype vehicle that was secretly flown between 1969 and 1973. Whether an FDL-5 vehicle was built and tested remains unknown and, officially, the FDL-5 never progressed beyond the mock-up phase.However, the enduring secrecy seems to suggest that a black budget prototype is a distinct possibility."[38]*

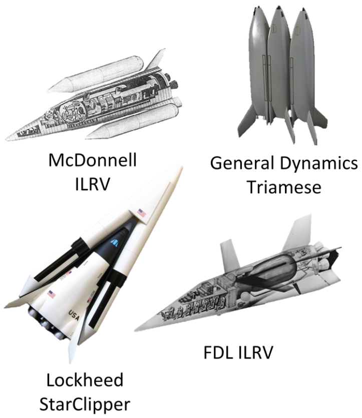


FIGURE A.8 – ILRV Concepts

### The ILRV Family

The USAF issued a number of design study contracts under the Integral Launch and Re-entry Vehicle (ILRV) program during 1967-68. The generic systems configuration would consist of a reusable single-stage VTHL RLV with expendable propellant tanks, quite similar to the Space Shuttle final design. Design proposals by Lockheed, General Dynamics, McDonnell-Douglas and FDL were mostly based of the lifting body second stage with differing launcher options for all the concepts. The Lockheed Starclipper utilized the FDL-5 type flat bottom lifting body as the orbiter stage with wrap-around drop tank[95]. FDL and McDonnell-Douglas also used a flat-bottom lifting body as the orbiter stage while the drop tank implementation was different than Starclipper [120]. General Dynamic's proposed design, the so-called Triamese was different from the rest in systems configuration implementation as it utilized three identical reusable booster/orbiter element vehicles rather than to develop two different booster and orbiter stages[121]. No original documentation could be located in the public domain for any of the proposals since the program did not proceed beyond the paper study phase since the proposals were considered too advanced for the time. The similarity with the Space Shuttle in the program requirement suggests a possible influence on the configuration selection as the Shuttle program was initiated just three years later. Figure A.8 shows the concepts studied during ILRV program.

**Experimental LRV projects: BGRV and Reentry-F** In addition to the lifting body evolution, a couple of experimental programs also investigated the hypersonic environment and technology. A follow-on to the 1957 Alpha-Draco, McDonnell's Boost Glide Re-entry Vehicle (BGRV) Model 122E, was developed from the earlier AMaRV missile program to investigate maneuvering at hypersonic speeds after reentry into the atmosphere. The program was highly classified as the bibliography of BGRV official reports in reference [[122]] classifies all reports as confidential.

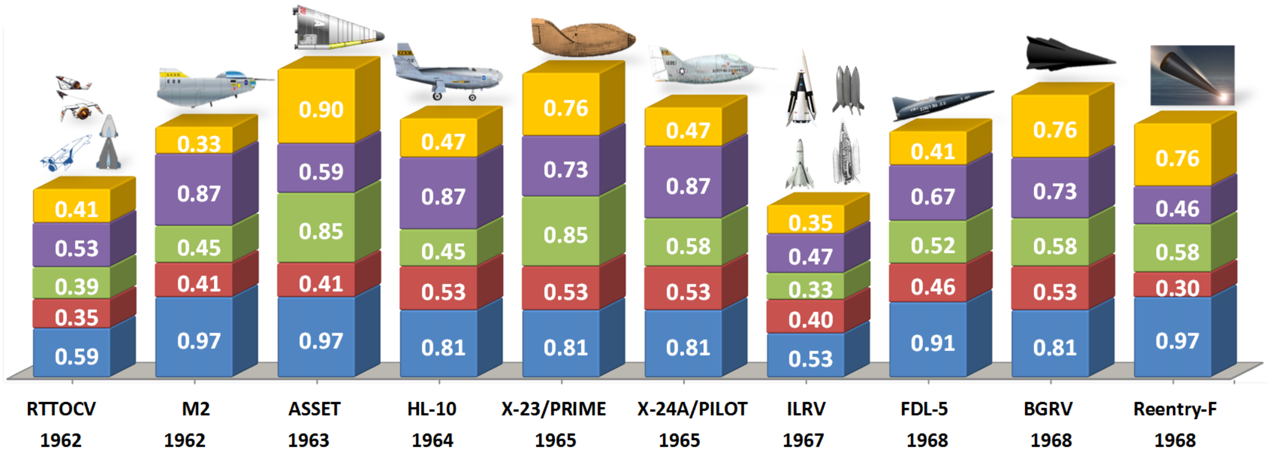


FIGURE A.9 – 1960s: AHP Evaluation

The following quote eloquently highlights BGRV's contribution:

> *" BGRV served to provide much data on hypersonic maneuvering flight characteristics. This data was of great value in developing later maneuvering re-entry vehicles. Upon re-entry into the Earth's atmosphere, flight control was achieved through the use of the aft trim flares and a reaction jet system commanded from an on-board inertial guidance system instead of by aerodynamic controls."[123]*

Similar to BGRV, Reentry-F was another experimental test vehicle flown to furnish experimental data on boundary-layer transition and heat transfer during reentry [124]. The data from this program are still used to benchmark theory and ground test data for the past 20 years [125].

These two experimental projects mark the end of discussion on the 1960s LRV programs. The evolution of this era is shown in Figure A.4, while the AHP assessment scores are shown in Figure A.9. The lifting body development continued under several programs in 1970s along with establishment of the Space Shuttle program.

### *A.1.3 1970s - The Space Shuttle Decade*

With the success of first moon landing in July of 1969, the US space program was looking forward to a golden era of Space. After five more successful manned moon mission, the Apollo program was terminated in 1972, the same year as the Space Shuttle program was defined. Before discussing the Space Shuttle, the continuation of X-24 program from NASA's lifting body program is addressed with, Figure A.10.

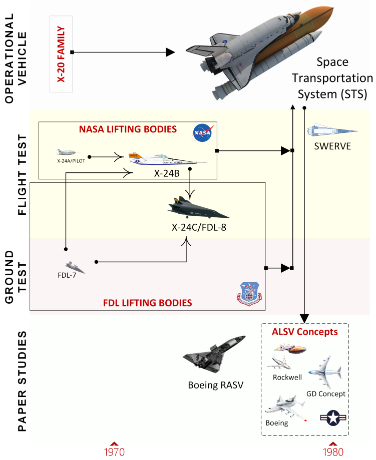


FIGURE A.10 – 1970s: LRV Evolution

### Continuing the Lifting Body Development: X-24B and X-24C

As discussed under the NASA Lifting Body program in the sixties, the development of X-24A began in 1965 within the START program, merging the USAF lifting body efforts with NASA. The X-24A had it's last flight in 1971 leading to its successor, the X-24B. While the previous generation of lifting body at NASA were round bottom designs, X-24B implemented the flat bottom design of FDL-7, a derivative of FDL-5. The X-24B program was developed as a low-speed piloted demonstrator for subsonic, transonic and supersonic testing used in the Space Shuttle[38]. The program conducted 32 successful flights, gathering important data for performance, handling qualities and stability & control characteristics. Following quote shows the significance of X-24B:

> *"The X-24B program was very successful and produced a number of test flights in a short time. This was attributed to using and the experienced engineering and flight test team from significant number the X-24A vehicle..The X-24B yielded Important information from all phases Of its flight and was the most efficient aerodynamic vehicle of the lifting body series as attested to by the flight test pilots."[119]*

The X-24B marked the end of NASA's lifting body program as the follow on vehicle, the X-24C was undertaken by the USAF alone. While the X-24B was based on the FDL-7, X-24C was an air-breather implementation of the FDL-8 lineage[38]. Several configurations of X-24C were explored by the FDL with scramjet and rocket powered versions, with the main goal to develop a new hypersonic scramjet-flight demonstrator reaching speeds upto Mach 8. Although the X-24C was cancelled due to tight budget constraints and the inability to identify a pressing nearâĂŤterm need for the flight facility, it is still considered as a significant milestone-effort to combine scramjet propulsion with a lifting body design, overall producing important data during the ground tests. Hallion's quote below is addressing the value of the X-24C experimental data:

> *"Eventually, XâĂŤ24C gained the distinction Of being the most extensively studied and analyzed "nonâĂŤflown" hypersonic vehicle."[33]*

The X-24C program was also considered for a proposed hypersonic testbed, the National Hypersonic Flight Research Facility (NHFRF), a vehicle that could have modular-type experiments for materials and various forms of propulsion, including scramjet test modules, implementing hypersonic cruising. The NHFRF program showed promise as several agencies expressed their interest in a next generation demonstrator, but failed to win support and was cancelled in late 1970's after one test-flight.[126] The X-24C marked the end of the lifting body effort in the 1970s as the Space Shuttle took center stage.

The Space Shuttle Program Definition The space Shuttle program was officially initiated in 1972 as the development continued for the rest of the decade with conributions from almost all major aerospace manufacturers. The Space Shuttle represents a converging and pivot-point for the lessons learned and technical progress made in the previous programs towards the first generation of an operational partially reusable LRV. Important contributions were made by the Shuttle in all the disciplinary criteria which are still used as a benchmark, particularly in the fields of rocket propulsion with SSME and thermal management with its tiles-based TPS[110]. The Shuttle is scored highly in all the discipline area as it was the first operational LRV program that implemented latest technology and paved a path towards the future generation of LRVs. The success of the program is an issue of debate, as the main objective while defining the program was to develop a reusable SAS that could provide a much less-expensive means of access to space.[96] Subsequently, this primary program requirement was not satisfied, as the Shuttle turned out to be much more expensive compared to the original hopeful estimates[127]. The Shuttle program was retired in 2011, after 133 successful missions and two failures of the Challenger at the launch and the Columbia during the re-entry phases. Even though the Shuttle was not a commercial success, it was the most advanced piece of technical ingenuity that played a key role in assembling the ISS, the Hubble telescope and served as the primary means of man-rated space access for the United States for almost three decades. It is by far the most documented LRV program; further specific details of its main contributions can be found in reference [[128]].

Other LRV Efforts Several other LRV programs were initiated by various institutions in the second half of the seventies, to further extend the capabilities of next generation SAS by utilizing the Shuttle as the starting point[42]. A 1976 Boeing initiative, the RASV program represents another such failed attempt. The company's interest in the reusable single-stage-to-orbit (SSTO) vehicle was*"..based on the belief that the reusable airplane type operation of earth orbit transportation vehicles will allow considerable improvement in cost per flight and flexibility."[129]* The program was cancelled after the paper study phase when the USAF started to focus its attention on the X-30 NASP. For further details on the RASV program, readers are advised to refer Dick and

Launius[42].

The USAF continued with the research on small spaceplane designs with the largely classified Air Launched Sortie Vehicle (ALSV) program[38], another precursor to the X-30. Proposals were submitted by Boeing, Rockwell and General Dynamics for the ALSV, which resembled Shuttle's configuration of a reusable LRV glider with expendable fuel tanks, but were launched by a modified aircraft as the first stage. There is little information available regarding individual proposals which hints that the program did not progress beyond paper studies, as the performance of the ALSV was not particularly impressive, while the technical challenges were daunting[130].

Following the lineage of experimental programs from the sixties, the SWERVE program was a maneuvering reentry body based on a slender cone configuration, with small wings and elevons[131]. Similar to the BGRV and Alpha-Draco programs, SWERVE provided much of the aerodynamic and aerothermodynamic experimental data from three test flights beginning in 1979[132]. Hallion recognizes the importance of these experimental vehicles in following quotes;

> *" ...the greatest contribution of programs such as the BGRV, Reentry-F, SWERVE, and FIRE (and, for that matter, the X-15 and even Shuttle later) was in highlighting the often great differences between predicted and actual performance, and the great need for more accurate ground test facilities, simulation techniques, and predictive tools..."[35]*

The AHP assessment and the evolution of the 1970s LRV programs is shown in Figure A.11.

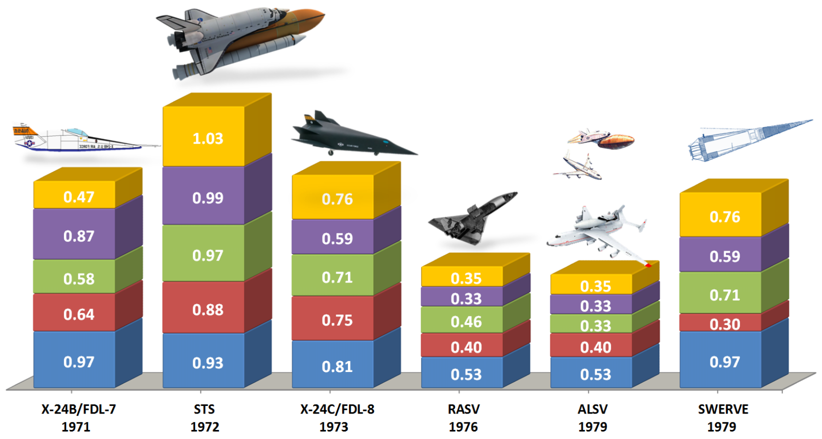


FIGURE A.11 – 1970s: AHP Evaluation

### *A.1.4 The LRV programs of 1980s*

Two case-studies from the 1980s are considered as major contribution towards the LRV evolution. First program was similar to the ALSV and ILRV programs of the previous decade, as the USAF *"..initiated a technology exploration program to examine small and easily maintained rocket-powered air-and-ground launched advanced hypersonic systems..."[35]*. This group of concepts called Trans-Atmospheric Vehicles(TAV)[133] were reminiscent of concepts proposed in the late 1960s and the early 1970s for the Shuttle program. The TAVs were envisioned as a new type of reusable launch vehicle with much broader operational capabilities, and application towards multiple mission categories[134]. The following quote by Rose support this notion further:

> *"It could take-off from normal runways as a conventional aircraft, it could be boosted on a sub-orbital flight using a Shuttle Solid Rocket Booster (SRB), or the TAV might be carried into orbit within the ShuttleâĂŹs payload bay. It was to be powered by one large rocket engine and two turbojets with options to reconfigure the propulsive system for different missions."[38]*

A workshop held at RAND to examine the TAV's mission, technical and design feasibility issues had the following remarks:

> *"..Discussions at the workshop and subsequent investigations reveal that despite the efforts of past programs, significant technology challenges remain, especially in the areas of propulsion, thermal protection systems, and overall vehicle integration...[134]"*

Another important LRV program from 1980s is the HL-20 lifting body envisioned as a Personnel Launch System(PLS) and later as a Crew Emergency Return Vehicle(CERV) to provide manned crew return complementing the Space Shuttle[135]. The vehicle was inspired by the Soviet BOR-4 lifting body, a test vehicle under the Soviet Shuttle program, the Energia Buran[38]. The NASA Langley personnel who worked on the 1960's lifting body program were also involved in the HL-20 development. the HL-20 conducted numerous aerodynamics investigations to improve low-speed characteristics of the vehicle to enable a horizontal runway landing. Further ground tests were conducted leading to a full-size mock-up model of the vehicle that furnished valuable data[136]. The following quotes form NASA confirms the value of the HL-20 research effort:

> *"..A significant amount of research effort has gone into experimental and computational investigations of the baseline HL-20 shape. The goal has been to amass a data base of information about this system to aid in management decisions for PLS development..."[137]*

Although the HL-20 was could not progress beyond the ground testing phase during the early '90s, it became the basis of the 2005 Dream

Chaser vehicle. This design is the only active LRV design to reach orbital capability is currently under development by the Sierra Nevada Corporation. Chiara has addressed the evolution of Dream Chaser from the HL-20 in reference [[138]] that was acquired by the author from Chiara himself and is available on the internet, but is not published officially in a journal or conference yet. The AHP assessment results and the evolution of the TAV and the HL-20 program included within the 1990s LRV case-studies are discussed next.

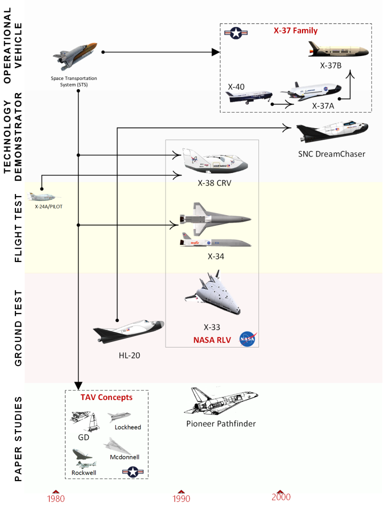


FIGURE A.12 –
1980s Onwards: LRV Evolution

### *A.1.5 1990s: Reusable Launch Vehicles*

The nineties started with the continuation of the HL-20 under the CERV program and showed a revived interest in the LRV design. A series of technology-demonstrator programs initiated by NASA in 1995 included the X-38 for the CRV, followed by the X-33 demonstrator for Lockheed Venturestar concept, and finally ended at the closure of the decade with the definition of the highly secretive X-37 program. But before these demonstrators, another concept that addressed the LRV design in the first half of the decade was a private initiative by the Pioneer Rocketplane, is discussed first.

THE PIONEER-ROCKETPLANE PATHFINDER FAMILY Pioneer Rocketplane[139] proposed concept for the Black Horse vehicle in 1993. The design was a match for the USAF TAV requirements, leading to paper studies at the USAF Phillips Laboratory. The initial design was further improved in the follow-up concept, the Black Colt, a one-crew SSTO launch vehicle powered by turbofan and rocket engines[140]. *"...Subsequent to the TAV workshop, RAND performed an independent analysis of Black Horse's payload capability and found it could not reach orbit...[134]"* The concept design from Black Horse and Black Colt was further refined with the Pathfinder Rocketplane design in 2001, but could not evolve beyond paper studies phase.

NASA REUSABLE LAUNCH VEHICLE EFFORTS Sometimes around 1994, the NASA Reusable Launch Vehicle (RLV) program was initiated, that resulted in four 'X-series' spaceplanes namely the: X-33 and X-34 under Reusable Launch Vehicle Program, and the X-38 for the CRV and the X-37 for the OTV program[141].

The X-33 program was initiated as a part of the RLV program in 1995 as a testbed for developing technologies for an integrated RLV design, paving the way for full-scale advanced commercial launch system[142], see Figure A.13. Lockheed Martin offered a VTHL lifting body concept based on the aeroballistic rocket, the VentureStar, and was selected by NASA against proposals by McDonnell-Douglas and

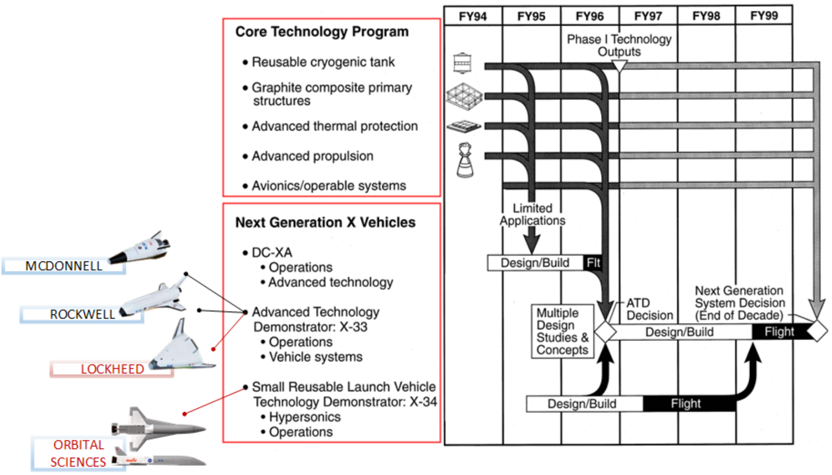


FIGURE A.13 – NASA RLV technology program schedule[142]

Rockwell [141]. The Venturestar proposed to use a linear aerospike engine, metallic insulation, and several other features similar to their Starclipper proposal[143]. Lockheed developed the X-33 as a technology demonstrator for the Venturestar concept and employed composite materials to reduce vehicle weight. This was one of the key requirements to successfully develop the Venturestar. However, the composite fuel tank failed during a testing in 1999 and it was concluded that composite technology was not mature enough at the time for such use in cryogenic reusable tanks[144]. This proved to be a fatal blow for the X-33 as program ran into cost and schedule overrun and was finally cancelled in 2001. The main lesson learned from X-33 was that the program accepted multiple technology risks, overall resulting in program failure. Related to the cryogenic composite tank and other aspects, the X-33 proved to be of significant value for the structure and materials discipline.

The next vehicle under the RLV program was the Space Shuttle-inspired X-34 technology testbed[145], a development by Orbital Sciences Corporation in 1996. It was planned to be an autonomuos vehicle, powered by a completely new reusable Fastrac engine, capable of reaching Mach 8 and performing 25 test flights per year[141]. The X-34 program too ran into cost and schedule overrun, similar to the X-33 as two unpowered flight test-vehicles were built spending just under $112 million before the program was cancelled in 2001 with the X-33. The following quotes by Sullivan show the main disciplinary contribution from the X-34 program:

> *"..The technological developments included autonomous ascent, reentry, and landing; composite structures; reusable liquid-oxygen tanks; rapid vehicle turnaround; and a durable TPS. The versatile flight testbed could accommodate future experiments, including space transportation and technology developments and*

*aeroscience experiments..."[146]*

Following the cancellation of the HL-20, NASA began developing X-24A derived X-38 research vehicle aimed at the development of technologies for a prototype emergency crew return vehicle(CERV). NASA was supported by the European Space Agency(ESA) through the DLR TETRA project for a common concept vehicle to satisfy their Space Station crew transport needs[147]. The program developed three test prototype vehicles conducting several autonomous test flights (horizontal parafoil runway landings) and tested technologies, for disciplines such as aerodynamics/aerothermodynamics, structures, TPS and flight control systems. European contribution to the X-38 program was found in all technical areas as the X-38 established first transatlantic venture for development of a reusable spaceplane[148]. The X-38 was eventually cancelled in 2002 due to budget cuts and could not result in an operational vehicle, but proved to be valuable for testing new structures and TPS materials improving aerothermodynamics database. Further details on the contributions by X-38 can be found in reference [149] and [150] .

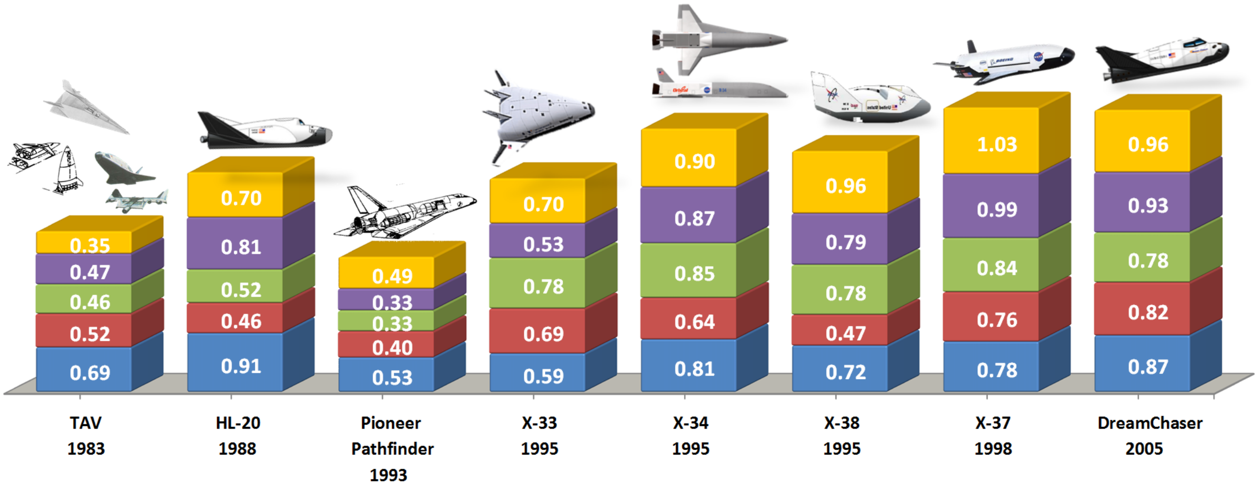


FIGURE A.14 – 1980s Onwards: AHP Evaluation

The X-37 program evolved out of the Boeing X-40 demonstrator for the USAF Space Maneuver Vehicle(SMV) under the Military Spaceplane Architecture program[151]. The first generation vehicle of the program was the X-37A Approach and Landing Test Vehicle (ALTV) and was used in drop glide tests in 2005-2006 by NASA[152]. The second generation Orbital Test Vehicle(OTV) or the X-37B, was developed and operated independently by the USAF and is currently operational, but remains highly classified regarding the details of mission details. The following quote by Grantz adequately represent the key technology and disciplinary contribution by the X-37 program:

> *"...Several key technologies for reusable spacecraft were successfully demonstrated in the areas of aerodynamics, aerothermodynamics, reusable solar arrays, Thermal Protection Systems (TPS) and autonomous Guidance, Navigation, and Control (GNC). The current system provides a demonstration platform for autonomous spacecraft technologies, on-orbit environments for material and microelectronic characterization and re-entry environments for advanced TPS materials and concepts..."[153]*

X-37 was the last LRV program initiated in the nineties and is the only LRV vehicle currently operational. The 1990s were a tough period for LRV programs where many bold initiatives were undertaken to establish a reusable SAS, but only the X-37 evolved to an operational vehicle status. The lessons learned were expensive and difficult but contributed immensely to hypersonic knowledge evolution. The evolution for the LRV program from 1980 onwards is shown in Figure A.12 and the AHP results for these case-studies are given in Figure A.14 that includes the last case-study, the Dream Chaser, which is discussed next.

### *A.1.6 Post 2000: The Dream Chaser*

The last US-based LRV case-study considered for this survey is the 2005 private initiative, SpaceDev's HL-20 inspired lifting body vehicle, the Dream Chaser[154]. The Sierra Nevada Corporation(SNC) acquired SpaceDev and took over the Dream Chaser vehicle in 2008. Two years later, Dream Chaser was selected for NASA's Commercial Crew Development (CCDev) Phase-1 program, as SNC continued with the ground tests, and further modified the design supported by funding and with technical cooperation from NASA[155]. The Dream Chaser was eventually dropped form the CCDev contract in the last seletion round and later selected under NASA's Commercial Resupply Vehicle program for a conract of six resupply missions to the ISS[156]. It is expected to be operational by 2018, delivering cargo and science experiments for NASA as the primary mission, although SNC is developing multiple variants for international customers as well[157]. The vehicle is developing and employing state-of-art technology in most subsystems[158–161], while building on the crucial aerodynamics knowledge base gained via the legacy HL-20 program. The AHP analysis results for the Dream Chaser is given in Figure A.14 with rest of the LRV programs form 1980.

A combined LRV evolution of the US-based case-studies is shown in Figure A.15 summing up the discussion of the US LRV history. Tracking the evolution through these historical programs helps to visualize, how the current Dream Chaser utilizes the hypersonic knowledge gained with incremental gains in individual program. The following section addresses the AHP assessment of the LRV efforts outside the US with a brief overview of major programs.

## *A.2 International LRV Case-Studies Assessment: Silvervogel - IXV*

Outside the United States, numerous LRV programs have been undertaken by several European and Asian countries. A total of 29 LRV case-studies from USSR/Russia, ESA, Great Britain, Germany and Japan have been assessed by the AHP model. In the following subsections, ESA, Germany, and Britain are discussed collectively under the European LRV programs, followed by a brief discussion of LRV programs in Japan and finally, Soviet/Russia.

### *A.2.1 European LRV Efforts*

Several lifting reentry programs were initiated during the early 1960s in Germany and Britain,[162] while post 1980s, ESA undertook several LRV-based research projects and technology development programs. The evolution of these European LRV case-studies is visualized in Figure A.16 and described in the further details as follows.

#### THE GERMAN LRV PROGRAMS

The concept of hypersonic LRVs dates back to as early as the 1930s, when Eugen Sänger in 1933 Germany, proposed the concept for Silberbogel(German for SilverBird) rocket plane. This was a definitive study, establishing the feasibility of rocket propulsion with airplane-like lifting configuration. Eugen was assisted by his future wife, Irene-Bredt, in further refining the design details in the later half of the decade. The vehicle was a rocket-propelled winged airframe, running on liquid oxygen and kerosene. It was proposed to be launched from a rocket-boosted sled to perform sub-orbital missions, reaching altitude of 100 miles, and achieving hypersonic speeds in order of Mach 10 during the reentry[163]. The Silvervogel concept underwent several wind tunnel and propulsion system tests by 1942 improving on the conceptual design studies. It was later found that vehicle would have generated unacceptable levels of airframe heating due to the skip-glide trajectory implementationa nd the low wing sweep angle, as this important issue had not been fully appreciated by Sänger and Bredt, and would have led to insurmountable problems if their project had gone forward[38]. The design concept was considered by Nazi Germany to be developed into the Raketenbomber or 'rocket bomber', but never evolved beyond ground tests until 1963 as Junkers RT-8-01. Further details on the Sil-

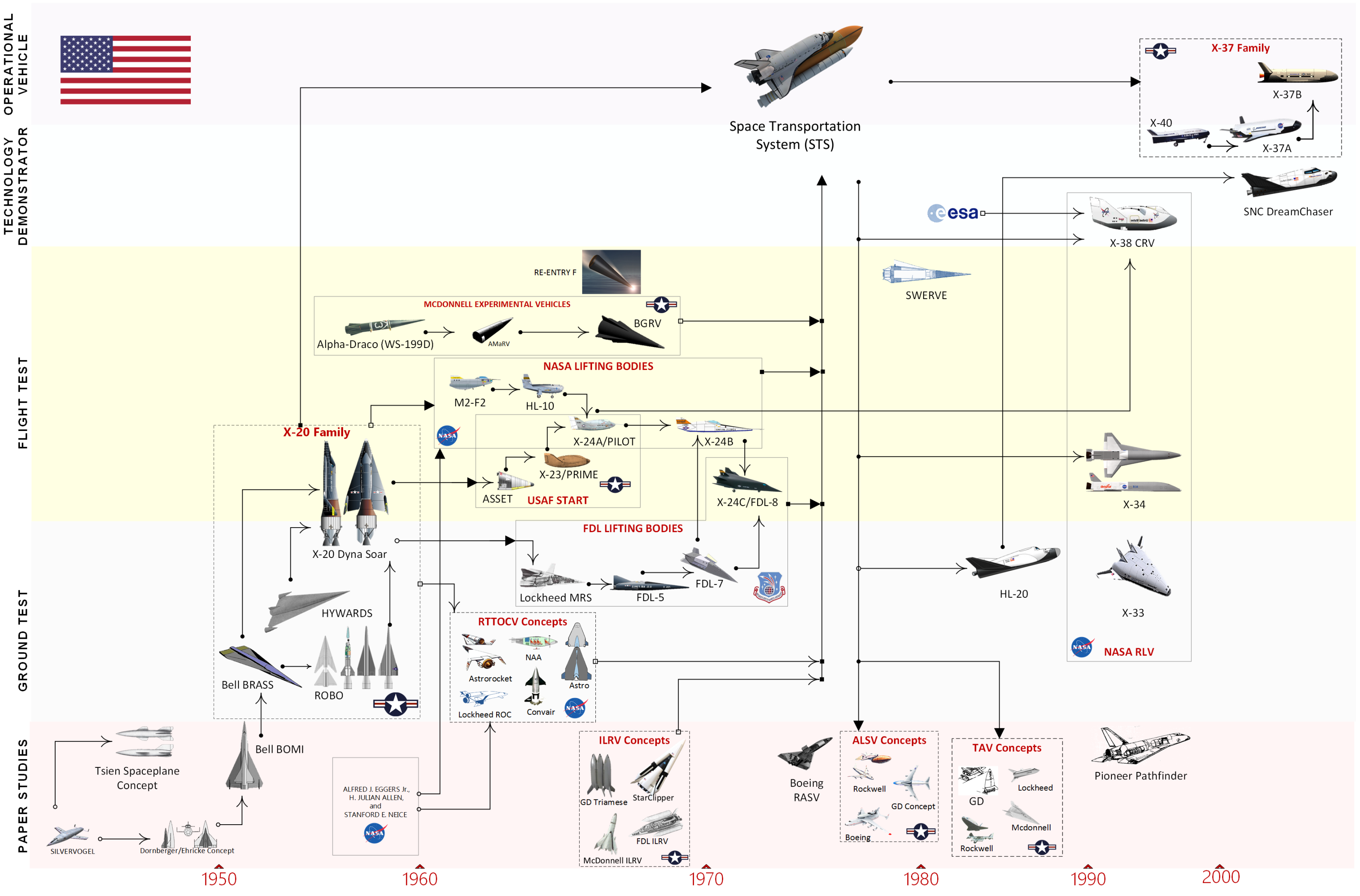


FIGURE A.15 –
US-based LRV Programs Evolution

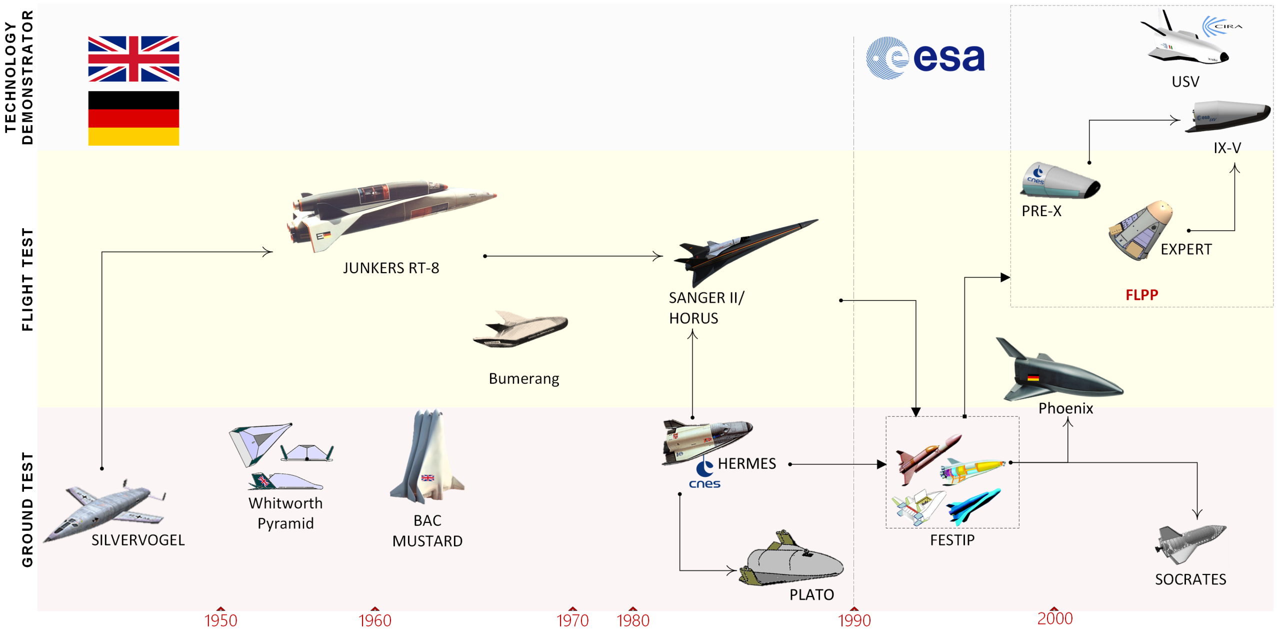


FIGURE A.16 – European LRV Programs Evolution

verbird and the follow-on designs can be found in reference [[18]], [[164]] and [[165]], authored by Eugen and Irene Sänger.

Between 1961 and 1964, Eugen Sänger was working with JUNKERS FLUG-ZEUG UND MOTORENWERKE (JFM) company in Munich on the Silvervogel follow-on design studies, for a sled-launched two stage space-plane system, the Junkers RT-8. Both, the first and second stages were delta-winged LRV designs, equipped with LOX/LH2 engines. The upper stage was a reversed version of the first stage launch vehicle, with the low-mounted wing, having upturned tips like that of the X-20 Dyna-Soar, and would be able to reach 300km altitude orbit[95]. Sänger was working on the RT-8 until the morning of his sudden death in February 1964. The design went through several iterations under Messerschmidt-Boelkow-Bloehm (MBB) as RT-8-02, but was eventually dropped in 1969. Eugene Sänger's work towards the LRV concept is undeniably the most influential contribution by an individual. He applied the rocket science fundamentals developed by Esnault-Pelterie, Goddard, Oberth and Tsiolkowski, into a practical concept, based on the philosophy of the so-called "school of Vienna", where Valier, Vonhoefft and Von Pirquet imagined aircraft capable of reaching orbital velocities[166]. Sänger's life was dedicated to the idea of realizing a rocket-plane to access space. A detailed account of his work is documented by his son Hartmut Sänger[166], who describes the importance of Sänger's legacy in these words:

> *"Eugen Sänger, however, was one of these rare, gifted engineer-physicists whose*

> *deep understanding of a technical knowledge which he partly created, combined with a real talent for large-scale project management, could turn some of these dreams into reality and, as such, help astronautics break the âĂIJscience-fictionâĂİ barrier."[166]*

Another major German LRV concept in the 1960s was the lifting body design, Bumerang. Developed by ERNO through a series of wind tunnel tests followed by unpowered flight tests, the Bumerang followed the contemporary NASA Lifting Body program and contributed to the Space Shuttle's project-definition phase with McDonnell Douglas[167]. Major contributions made by the Bumerang were in the disciplines of aerothermodynamics, thermal management, and sub-systems as found in the detailed description in reference [[168]] and [[169]].

In 1985, MBB began renewed studies of the Sänger spaceplane, this time, a two-stage-to-orbit horizontal takeoff concept. The first stage was a turboramjet powered delta-wing design, for boosting the orbiter vehicle called HORUS, which was based on the CNES Hermes vehicle[170]. The program was the reference concept of the German Hypersonics Technology Program and achieved major results in disciplines of propulsion, structures & material, subsystems and aerothermodynamics[171]. However, the propulsion research was mainly concentrated on air-breathing launch stage, which proved unsuccessful in developing a feasible propulsion system and the program was terminated in 1995 due to budget cuts. Sänger II concept was also studied under the FESTIP program by ESA and further details of the vehicle system and major contributions are found in references [[171]] and [[172]].

In 1987, ERNO and MBB started working on a winged LRV design called The Platform Orbiter or PLATO for short. The program emerged out of Europe's desire to not be dependent on the US Space Shuttle for orbital access, as PLATO was planned to be launched by European Ariane 4 rocket from Kourou, French Guiana, and land horizontally in southern Europe[173]. Several wind tunnel activities and trajectory simulation models were developed for PLATO. However, the program could not develop beyond these ground tests and was cancelled in 1990. References [[174]] and [[175]] are some of the best sources found for this project, describing the research effort development under the program.

PLATO concludes the discussion of LRV programs initiated in Germany. Figure A.17 shows the AHP results of the Germany LRV programs along with the British concepts, Whitworth Pyramid and BAC MUSTARD, which are discussed next.

### The British LRV programs

Two British programs are seen to fit the LRV class and are analyzed

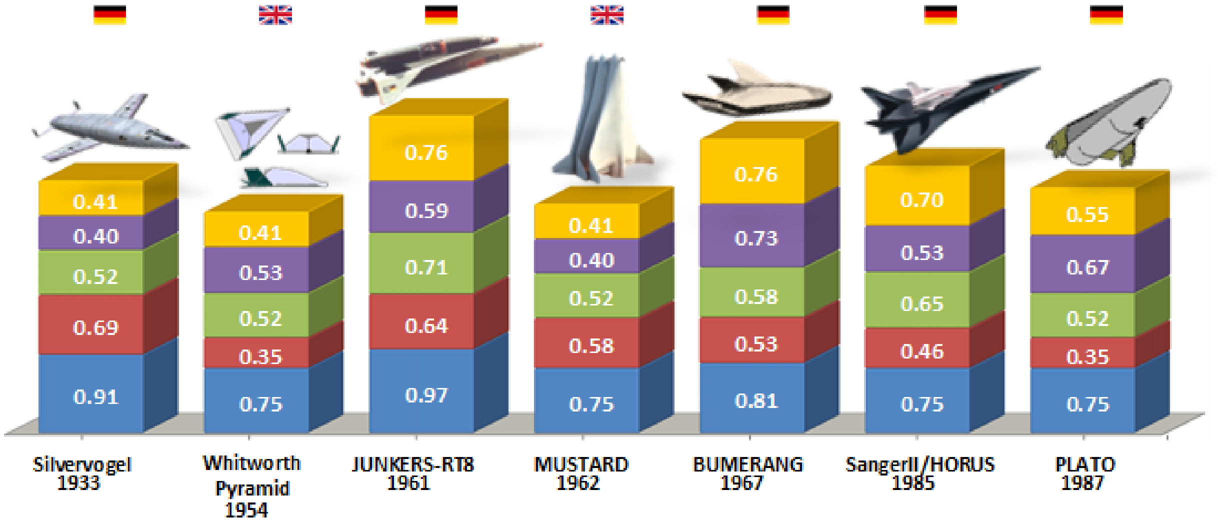


FIGURE A.17 – German & British LRV Programs: AHP Evaluation

here in the AHP model. The first study originated in 1954, an unusual pyramid-shaped design with a flat underside and short wings, was developed by Nonweiler following the development of his famous wave rider concept. Rose[38] provides further details for this design development, which suggests the vehicle made developments in aerothermodynamics and subsystems disciplines through a series of wind tunnel tests, leading to various design modifications. The vehicle could not evolve beyond that stage and was cancelled in 1960. During this period, the British Aircraft Corporation (BAC) was conducting studies for developing a small British spacecraft using delta-winged designs. Following on its initial hypersonic and spaceplane studies, the BAC began work on the government funded studies aimed to develop a reusable manned Orbital Transporter. Inspired by the American lifting body design and the modular concept as implemented in the McDonnell Astro and Convair Triamese, program MUSTARD was defined in 1962. The vehicle configuration resembled closely the Convair Triamese design using three identical lifting-body stages. Although no technical report has been available for MUSTARD, several FLIGHT magazine articles and two patents filed by BAC[176, 177] in 1969, reflect that MUSTARD developed ground-test articles and made significant progress in propulsion and aerothermodynamics disciplines[178]. The AHP results for these two programs are given in Figure A.17 with German programs.

LRV PROGRAMS FROM ESA The European Space Agency (ESA) was established in 1973 following the reforms made to previous European space collaboration under ESRO and ELDO[179]. The LRV case-studies evaluated for ESA represent a collective effort of several European national space agencies from the 1980s onwards, starting with the French program, Hermes.

The first LRV case study considered as a joint ESA project is the 1985 Hermes program, originated in the second half of the 1970s within the French Space Agency CNES[180]. Inspired by the US Space Shuttle and the X-20 programs[38, 181], the project started with the basic idea of realizing a small manned space plane was a winged reusable reentry vehicle to be launched on top of the European Ariane-4 launcher. Its sole original purpose was the transport of two to four astronauts into low Earth orbit (LEO) as a kind of 'space taxi' for autonomous missions. However, since the beginning of the program, the need for a European manned space capability was not clearly specified as the basic requirements and underlying specifications were changed more or less continuously. The focus of the program shifted from an operational space transportation system towards a manned experimental space vehicle and finally a pure technology demonstrator before being cancelled in 1992 owing to the mass budget complications [181]. Bayer further elaborates; *"..After years of development of Ariane 5 and Hermes, the most basic requirement of the compatibility of the payload mass with the launcher had still not been achieved despite the fact that the transport of Hermes was one of the primary design missions of Ariane 5. In general the configuration chosen for Hermes was not adequate for the multiple demands posed on it, and the absolute size of the vehicle was too small for the required functions..."[181]* Although the program could not develop a feasible SAS, a considerable amount of technology-specific research was conducted while the program was active, especially in the disciplines of aerothermodynamics, thermal management and subsystems development.[170, 182–184]

The Hermes configuration show uncanny similarity with the X-20 program as both programs shared similar mission requirements, design configurations and were cancelled due to similar reasons. The program was a crucial learning curve for the ESA partners and has been studied and documented extensively for major lessons learned in organizational, programmatic and technical aspects.[181, 182].

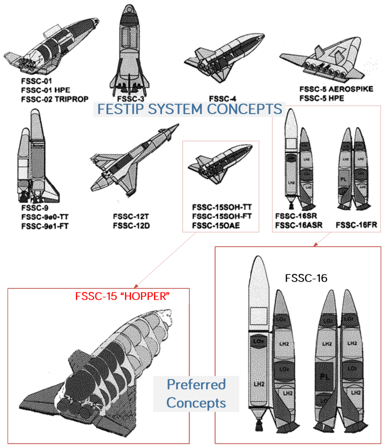


FIGURE A.18 – FESTIP Concept Studies and Final Selection. Reproduced from [185]

Utilizing the lessons learned from the Hermes experience, ESA decided to perform a detailed concept investigations on a commonly agreed basis among the participating nations, with closely related technology preparation under FESTIP. The primary objective was stated as: *''..FESTIP will enable Europe to take decisions on the development of a next generation launcher."[186]* The FESTIP program was defined in 1994, comprising a system study as the focal point, and five technology studies in the key technology areas[185]. Readers are reminded that the five disciplinary criteria selected for the AHP model implemented in this study were borrowed from FESTIP's definition. The FESTIP program played a key role in defining common goals among participating agencies to provided a path for maturity of key technologies[187, 188]. Several vehicle concepts were analyzed during the initial configuration selection phases as shown in Figure A.18. Following the initial evaluation, concepts FSSC-15 and FSSC-16 were preferred on the basis of technical feasibility and economic viability[45]. Technical feasibility and mission performance were claimed to be achieved by all concepts and further details on individual system concepts can be found in references [[189]] and [[190]].

In 1998, the FESTIP team selected FSSC-15 HOPPER as the final concept and decided to pursue detailed design work within planned Future Launcher Technology Programme(FLTP), foreseen for 1999-2005. Based on the configuration of the HOPPER concept, the German ASTRA program started developing the Phoenix test vehicle as the EXTV option for FESTIP[191]. The main objective was to demonstrate fully autonomous approach and landing for an RLV-like configuration, possessing relatively poor low-speed flying qualities.[151] In 2004, the vehicle executed the only drop-test flight, executing a fully autonomous landing. A part of the FLTP objectives was to develop and validate the required technologies for the HOPPER vehicle. But unbalanced participation in the program by various member states and the consequent problems with implementing procedures resulted in the FLTP being put on hold[192], and eventually canceled, along with the suborbital HOPPER concept and its sub-scale test-bed vehicle, the Phoenix. Another testbed vehicle based on the Hopper's configuration was the SOCRATES program with goals to demonstrate most RLV mission phases, from autonomous takeoff to abort capabilities.[151] Apart from the major objectives and initial program definition requirements, not much information is found on this proposed testbed, now assumed to be abandoned after the cancellation of Hopper.

Following the FTLP debacle, the Future Launchers Preparatory Programme(FLPP) was initiated in 2004 to prepare the next generation of launchers, starting with system studies carried out under FESTIP. During the next phase of the program, FLPP initiated *"..a progression of test vehicles to explore the physics of, and demonstrate the capability to accomplish, controlled reentry flight..[193].* The first of these programs was the European eXPEriment Reentry Testbed(EXPERT), intended to gather data on reentry aerothermodynamic phenomena using a geometrically simple, but highly instrumented non-maneuvering reentry vehicle."[151] EXPERT was supported by several aerothermodynamics facilities throughout Europe, equipped with 14 experiments provided by several scientific institutions all around Europe[194, 195]. EXPERT performed several flight tests as a precursor to the IXV technical

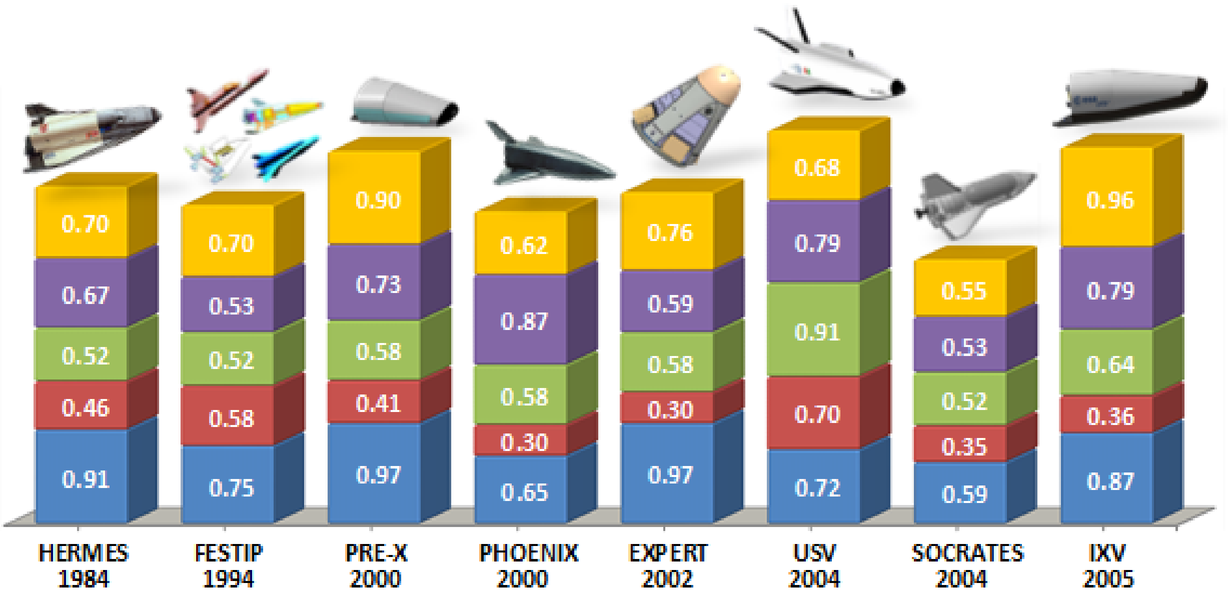


FIGURE A.19 – ESA LRV Programs: AHP Evaluation

demonstrator, providing important data for aerothermodynamics and thermal management disciplines.

Another program leading to the FLPP IXV began in late 2000 when the French space agency, CNES, began with preliminary assessments of a lifting testbed called the Pre-X. The main objectives were defined to develop and demonstrate technologies in thermal management, aerothermodynamics, and subsystems disciplines[196]. Following the initial preliminary design period, Pre-X has undergone extensive detailed design analysis and ground testings to develop the vehicle, in order to comply with in-flight experiments plans[197, 198]. The Pre-X configuration became the basis of the FLPP-IXV demonstrator.

A significant LRV effort under the FLPP initiative was the CIRA (Italian Aerospace Research Center) program, PRORA-USV, "to develop and flight test technologies critical to future-generation reusable launch systems."[151] The vehicle conducted technology demonstration flights providing a valuable system and subsystem feasibility insight. Ruso[199, 200] provides further details of the program's main objectives and major contributions to the disciplines of subsystem and structures. These trends are also seen in the AHP results.

During the Period-1 stage of the FLPP program, the industrial systems team was tasked to select the most promising ongoing studies for the Intermediate Experimental Vehicle (IXV). As mentioned earlier, CNES Pre-X was selected as the optimum design and the IXV adopted the external configuration of the Pre-X[201]. Multiple goals identified for the IXV were: *"..demonstrate hypersonic unpowered maneuvering reentry flight of a lifting configuration, serve as a test-bed for in-flight qualifica-*

*tion of vehicle subsystems and systems, and to provide another source of data on fundamental hypersonic aerothermodynamic phenomena for validation of tools, databases, and design processes.."[151]* With these goals, the IXV was to develop on the in-flight research conducted by the EXPERT program[202]. The IXV flew on its successful maiden test flight in 2015, producing important aerodynamics and thermal data. The program is scored high on aerothermodynamics, thermal management, and subsystems disciplines and is planned for the follow-up flights in 2019/2020[203]. The IXV is the last case-study considered for the ESA-initiated LRV efforts, most of which saw fruition as technology demonstrators for the next-generation reusable launch vehicle. The AHP results for the ESA case studies are shown in Figure A.19.

### *A.2.2 LRV Efforts in Japan*

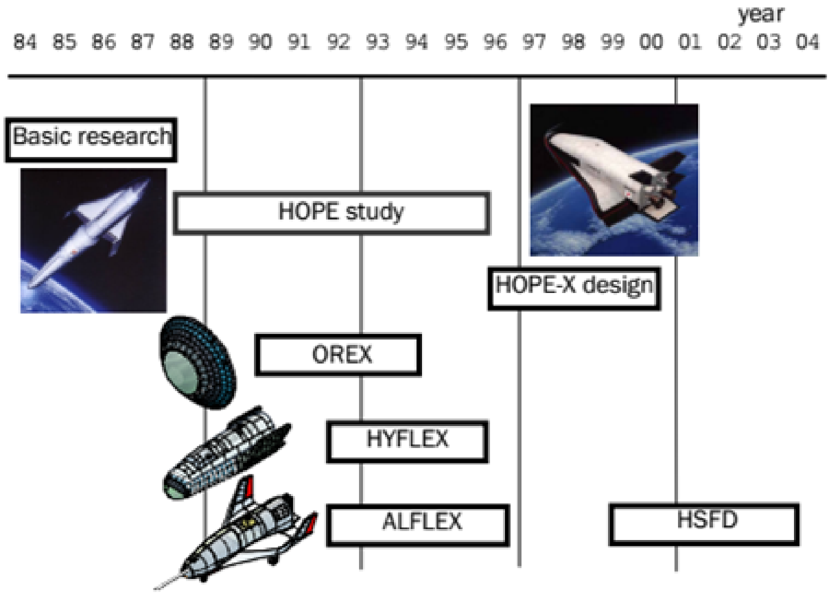


FIGURE A.20 – HOPE-X Program Timeline[204]

The LRV research efforts in Japan are focussed under the HOPE(The H-2 Orbiting Plane) program started in the 1980s by NASDA and NAL (both now part of JAXA). Following the early paper studies, the development plans led to the HOPE-X, a full-scale demonstrator for the operational HOPE vehicle. *"..Although the size and configuration of HOPE-X duplicate the operational HOPE, its gross weight will be about two-thirds of operational HOPE..."[205]* Three experimental projects were defined initially during the early development plans that would lead to HOPE-X as each project would focus on specific disciplinary development. A fourth vehicle was added to the initial three experimental projects during the later program stage. The HOPE-X program evolution and experimental projects timeline are shown in Figure A.20, borrowed from Miyazawa[204], and are explained in the following discussion.

The OREX flight experiment, first in the series of HOPE-X precursors, was a blunt-cone shaped vehicle. After the early development phase, the OREX vehicle flew successfully in 1994 and provided important aerothermal data (wall temperatures and heat transfer rates) for the design of the TPS for HOPE[206].

The OREX was followed by the Hypersonic Flight Experiment or HYFLEX, an unpowered lifting body that resembled the original HOPE-X configuration, unlike the conical OREX. The main objective of the HYFLEX was to explore guidance and control aspects of a lifting body and to utilize the aerothermal data from OREX by testing the TPS materials and structures[207]. HYFLEX conducted a successful flight in 1996, testing the carbon-carbon heat shielding tiles that were intended to be used on HOPE, and provided data on hypersonic lifting, although the vehicle sank in the Pacific after splashdown before it could be recovered[208].

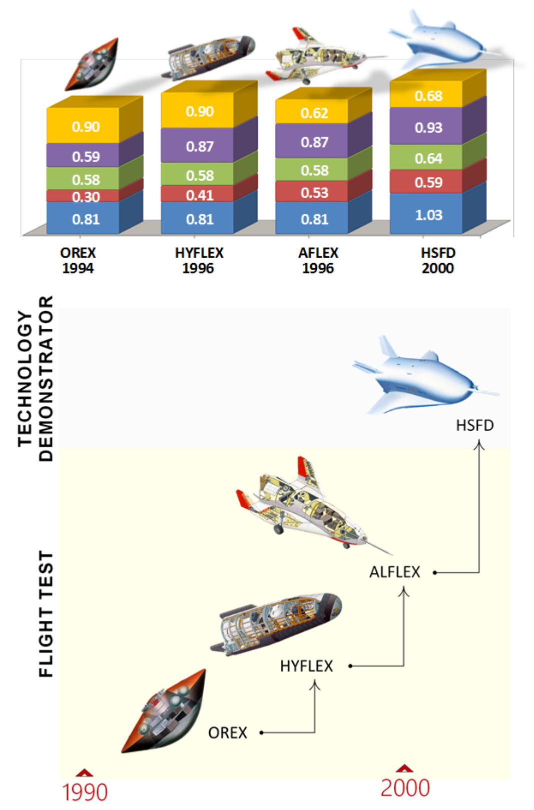


FIGURE A.21 – Japan LRV Efforts under HOPE Program

ALFLEX, the last experimental project planned under HOPE-X was a one-third model of HOPE with a primary goal to develop an unmanned landing system for HOPE-X. *"The ALFLEX flight tests were successfully conducted at Woomera in Australia in July and August of 1996* *with the cooperation of Australian government. Approximately 20 flight tests were done to evaluate guidance performance, aerodynamic characteristics and performance."[205]* Both, HYFLEX and ALFLEX are scored high on the aerothermodynamics and subsystems disciplines for their contribution in stability and control during the landing, while OREX is scored high on the thermal management and aerothermodynamics disciplines.

In addition to the originally defined three experimental projects, the High-Speed Flight Demonstration (HSFD) program was added later in the HOPE-X program. The HSFD vehicle was a 25-percent scale test model of HOPE-X, defined with an objective to test technologies for the development of a future reusable launch vehicle.[209] The HSFD program conducted successful test flights in two phases, *"..Phase I to verify an approach and landing system for the return flight of a winged reentry the vehicle that lands on a conventional runway, and Phase II to clarify the transonic aerodynamic characteristics of a winged reentry vehicle..."[210]* The HSFD flight test played an important role towards aerothermodynamics and sub-systems disciplines. The HSFD program is the last Japan-based case-study assessed in the AHP model and further information about the vehicles and test flight results are found in reference [[210]].

Following the success of these experiments, HOPE-X design development continued from 1996 to 2000 during which the configuration changed from using wing-tip fins to twin canted fins on the aft fuselage[211]. The HOPE-X vehicle was being developed to be launched using the new H-II launch vehicle. However, due to launch failure of the H-II vehicle in 1998 and 1999[212], the HOPE-X program was frozen in the middle of 2000 and eventually cancelled in 2003[204]. HOPE-X is not included in the survey as the technology projects defined under the HOPE-X program provide more specific data and information than the unrealized HOPE-X.

The four case-studies from Japan are shown in Figure A.21 with respective results from the AHP model.

### *A.2.3 LRV Efforts in Soviet USSR*

The Soviet Union has been involved in the LRV design since as early as 1956 when Myasishchev began studies for a manned spaceplane. The primary objective was similar to the United States contemporary program X-20; to execute piloted orbital military operations. This was followed by a series of small VKA designs eventually leading to an aerodynamically more efficient VKA-23 Design 2, after a major re-evaluation of the initial faceted wave riding configuration Design 1[38]. Matthews elaborates further: *"The second Myasishchev VKA-23 design was an elegant-looking, porpoise-fuselage winged vehicle, similar to Japan's*

*HOPE design of forty years later. In comparison to the faceted first design, this version had a greater fuel load, much greater orbital maneuverability, and dispensed with the landing skis."[213]* The study reached detailed design stages with selection of specific components for vehicle structures & materials, TPS and GNC disciplines.[214] The design could not progress beyond ground test phase and was cancelled in 1960 leading to the OKB-Rocketplane, which further explored the VKA's program objectives.[215]

The OKB bureau overtook VKA 1960s objective to develop a manned military spaceplane to perform orbital reconnaissance and intercept American satellites.[214] Several design concepts were studied including X-20 look alike delta-winged configurations, the most prominent one was the Racketoplan. The program conducted flight tests of aerodynamcally controlled vehicles, that came about two years before the USAF START program. This was the first ever hypersonic reentry test and provided important data that was utilized in various OKB designs.[215] The Racketoplan was cancelled in 1965 as the Spiral became focus of LRV concepts.[38] Further detailed information on the project is found in reference [[37]] and [[216]]

Spiral OS refers to the first generation of a design concept in a series of the Spiral 50-50 family[217] which began in 1965 following the cancellation of Racketoplan. The OS orbiter concept was a lifting body configuration with flat bottom implmenting unique dihedral wings and was the baseline design which evolved in test vehicles, the Mig-105 and BOR family. The Sprial OS design was refined via wind-tunnel tests, while the program underwent several organizational changes in the early to mid 1970s. In 1975, the OS design was designated Experimental Piloted Orbital Aircraft(EPOS) and referred to an atmospheric flight test article, the Mig-105[38]. The vehicle incorporated several design features and subsystems technologies from the OS design including a flat bottom lifting body configuration. Mig-105 conducted eight subsonic flights from 1976 to 1978 and were considered sufficient to characterize the spaceplane's subsonic aerodynamic characteristics and air-breathing propulsion systems. Another important LRV research project defined under the Spiral-family was the BOR(unpiloted orbital rocketplane) family of test vehicles. BOR-1,-2 and -3 conducted suborbital flight tests from 1968-1969 for the Spiral program. When Spiral was cancelled in the wake of the Buran program, BOR-4 was already being developed to test heat shield materials, and was included in the Buran program. BOR-4 conducted four successful test flights where it confirmed the feasibility of the selected heat shield tile's materials and provided important data on the acoustic environment during launch and re-entry. BOR-4 was the last resulting vehicle from the Spiral program which generated critical data, technology and momen-

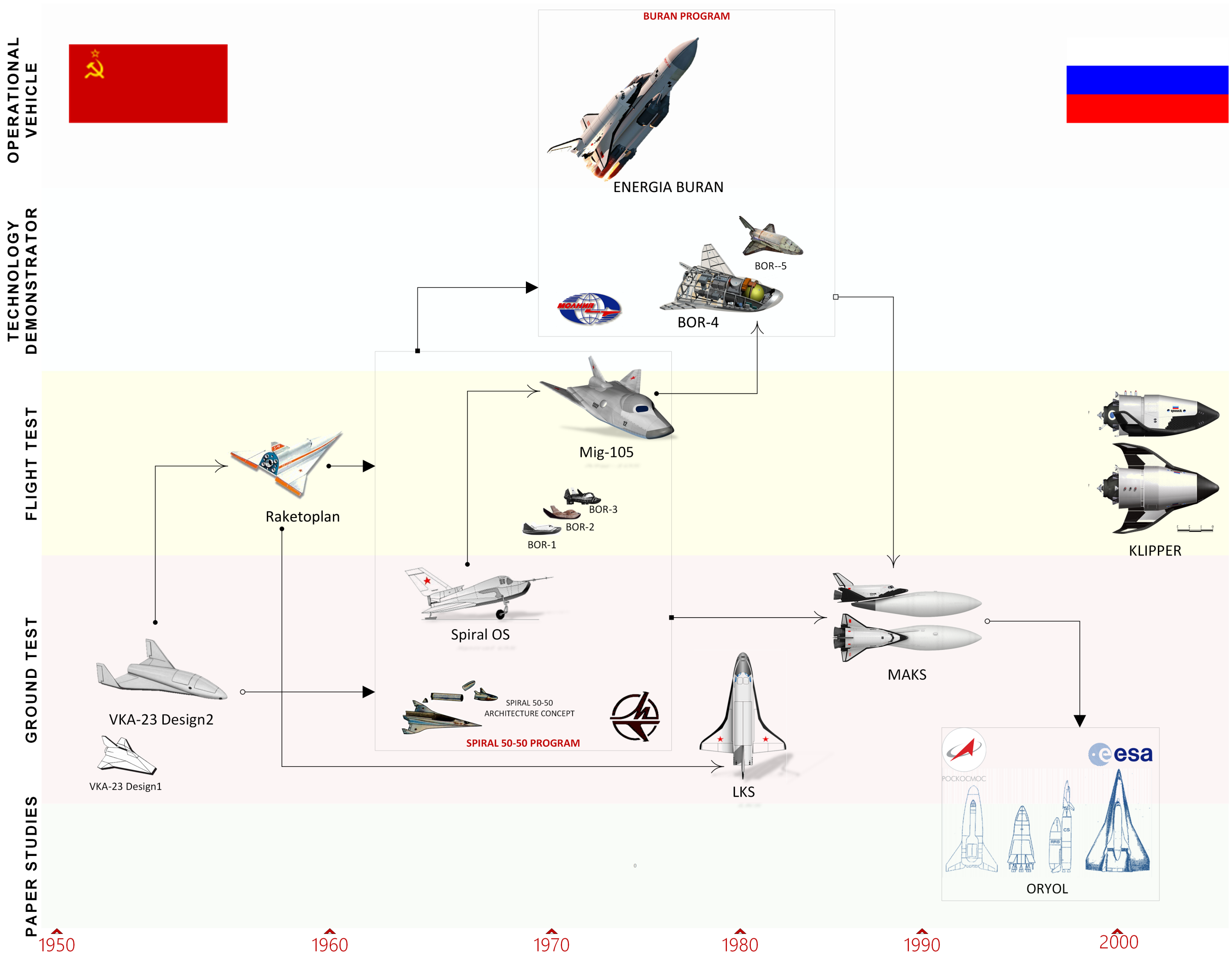


FIGURE A.22 – USSR/Russian LRV Programs Evolution tum that was utilized in the Buran vehicle. However it was resurrected in improved form in the 1980's as the MAKS spaceplane.[37, 38, 217] The following quote by Siddiqi highlight the importance of the Spiral program:

> *"The Spiral project was huge, much larger than any of the previous spaceplane programs in the Soviet Union, certainly rivaling and perhaps exceeding the amount of effort the U.S. Air Force had invested in the Dyna-Soar program. The rich historical legacy of spaceplane research in the USSR, leading all the way back to the Sänger-Bredt studies in the late 1940s. served as a springboard for the new project."[37]*

The Soviet Shuttle program, Buran was established in 1976, in response to the definition of the US Space Shuttle in 1972 and is as well known as it's American counterpart. Buran represents the pinnacle of LRV effort in Soviet/Russian case-studies and developed and implemented state-of-art technology in most subsystems. Buran conducted only one unmanned orbital flight in its operational term and demonstrated a fully-automated landing. Buran's significance is highlighted by the following quote:

> *"..The development of Buran went on 10 years. Ten years during which important research tasks and experiments were carried out in various technical fields: acoustics, thermodynamics, systems design, dynamics of flight on simulator, design of the control panel, making of new materials, developing of methods and equipment for the landing in automatic mode (flying laboratories), atmospheric flight tests of the similar shuttle (another model of Buran with turbines, BTS-002), outsides tests of the heat shield and aerodynamic tests on BOR-4 and BOR-5 models, etc..."[218]*

'Energiya-Buran: The Soviet space shuttle'[215] by Hendrix and Vis and the internet website in reference[[218]] are some of the most comprehensive account of the program and must be referred for further detailed information.

While the Buran program was in its peak during the late 1970s, Professor Chelomei from OKB-52 developed designs of a manned spaceplane based on his earlier cancelled Raketoplan program. The design was called the Light Space Plane (LKS) and plans for a prototype were completed by 1980. The LKS final design *"..had a launch mass of 25 metric tons, including 4 to 5 metric tons of payload and 2 metric tons of maneuvering propellant. Maximum use was made of actual flight test data from the MP-1 and M-2 sub-scale Raketoplan vehicles flown in the early 1960's. Major spacecraft systems were off-the-shelf items developed for the Almaz / TKS space station (e.g. engine section, guidance elements, environmental control system, thermoregulation system, heat shield, reusable equipment)...In 1980 the 25 volume technical specification for the complete LKS system was completed, a full-size mock-up was built, and a 15 volume construction plan for a fleet of LKS orbiters was prepared."[219]* Although the program reached mock-up model stage showing a promising outlook in design feasibility, it was cancelled in 1983.

MAKS was a scaled down version of Buran, that emerged out of studies from Project OK-M in the early 1980s. The highlight feature of the MAKS concept was it's capability to undertake a range of varied missions and could be launched vertically using a booster or air-launched atop a modified Antonov An-225. The air-launched proposal evolved into a more sophisticated design which was selected as the final MAKS configuration combining a reusable winged orbiter and expandable fuel tanks. This design concept closely resembled the ALSV program going on in the US around the same time. One of the main technical achievement from MAKS was the Glushko RD-701 tri-propellant engine, specifically developed for the MAKS program. The propulsion system would initially use kerosene and LOX and then switch to liquid hydrogen and LOX to provide a higher specific impulse. For other sub-systems like the TPS material or the autnomous reentry, MAKS utilized the research base developed in the Buran program. The MAKS design reached mock-up model stage and most of the hardware for the demonstrator, MAKS-D was completed[221], when MAKS was cancelled in 1991 owing to national economic difficulties.[38, 222]

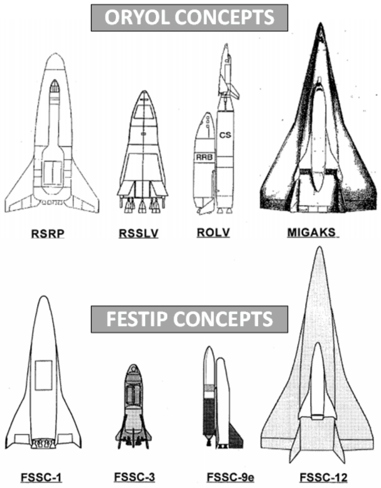


FIGURE A.23 – ORYOL program concepts selected for comparison with FESTIP. Reproduced here from [220]

The ORYOL program was initiated by the Russian Space Agency in 1993 as a research initiative to devise a stratergy for the development of the next generation of reusable space transportation systems. The study focussed on SSTO and TSTO orbital concepts based on a winged flyback and expandable second stage as air-launched systems were also considered through MAKS design.[223, 224] In terms of program objective and approach, ORYOL shared many similarities with the concurrent European FESTIP program, establishing an official cooperation between the RSA and the ESA in 1995.[220] Both programs assessed similar system configuration concepts independently considered before the cooperation. These system concepts were compared and assessed against each other and *"...led to a better understanding of both sides' approaches and requirements and to the recognition that the resp. technical views are rather compatible."[220] Figure A.23 shows the concepts compared from ORYOL and FESTIP. The program was finished in 2001 with a general conclusion that best option to approach the next generation of space transportation system was to develop partially reusable TSTO system with flyback boosters and conventional rocket engines.[215]*

The Kliper program was defined in 2004 as a replacement option for the Soyuz spacecraft. The initial concept proposed for the vehicle was a pure lifting body design that evolved to a lifting body with fold-able wings following several iterations to meet the requirements implemented by the upgraded Soyuz-2 rocket. Kliper had a unique

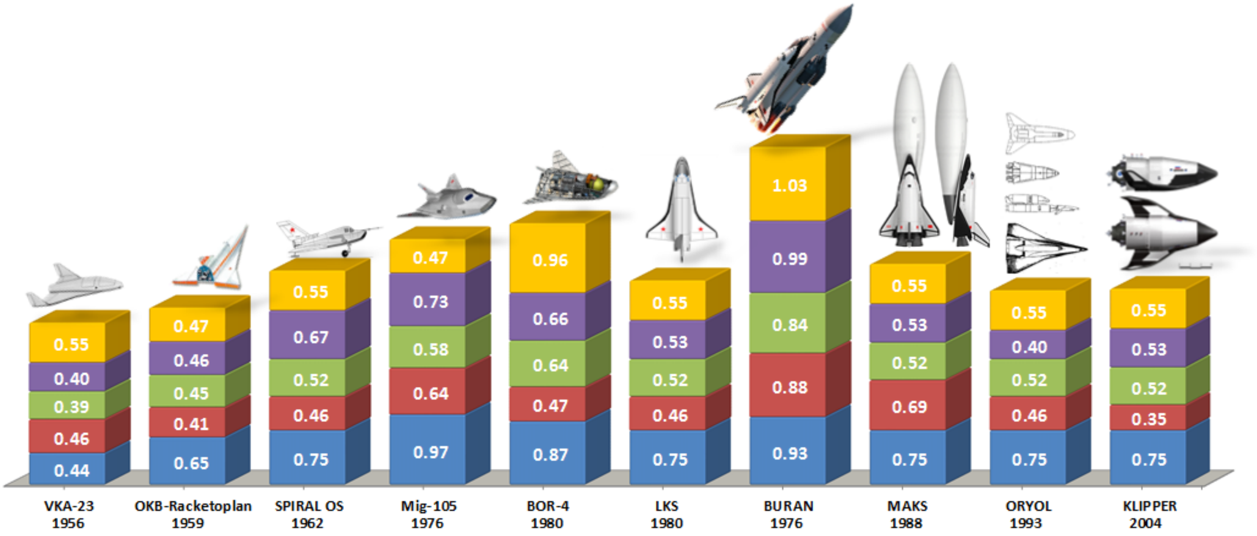


FIGURE A.24 – Soviet/Russian LRV Programs: AHP Evaluation

configuration, unlike previous lifting bodies it was short and stout with a detachable habitation and service module mounted behind the glider. RSC Energia developed the design from 2006 onwards without Russian government's support and tried to seek private investment but failed to do so, as the program has been officially halted since 2007 with no signs of revival.[218]

The Kliper marks the end of the discussion for the USSR/Russian and the international LRV case-studies. The AHP evaluation of the Russian case-studies are shown in Figure A.24 that compares the disciplinary and overall contribution.

*Appendix B*

# DISCIPLINARY ANALYSIS METHODS

This section presents the MATLAB codes as used in the disciplinary analysis for involved disciplines. The codes shown here only present the analysis segment as the DBMS manages the input and output variables in the MS Access system. Once the sizing architecture is assembled by specifying individual methods, DBMS inserts the variables around the analysis code structure as specified within the architecture.

## B.1 Geometry Methods

Three distinctly different geometry methods have been used for the sizing analysis.

### B.1.1 Geometry Calculation: X-20 Dyna-Soar

```

%*************************************************
%DynaSoar X20 Geometry Definition
%Author : Loveneesh
%
    *****************************************************************
% ——— Variable List ———
%
    *****************************************************************
% ————————————
% INPUT
% ————————————
% SPLN (m^2)          Glider planform area
% TAU                 Glider slenderness ratio
% ALLE                Leading Edge Sweep Angle
% DIA_NOSE     (m)         Nose Diameter
% LTD                 Ratio Glider total length to diameter of half
    cylinder fuselage
% WTD                 Ratio Wing thickness to diameter of half
    cylinder fuselage
%
% ————————————
% OUTPUT
% ————————————
% AL(m)               Vehicle Length (m)
% DIA_FUSE(m)         Vehicle Diameter
% BPLN(m)             Span of the vehicle
% SWET(m^2)           Wetted surface area
```

```
% SFSPLN          Ratio of frontal area to planform area
% SF(m^2)         Frontal area
% AKW       Ratio of wetted surface area to planform area
% AKWo            Ratio of wetted surface area to planform area of vehicle without spatula
% *************************************************************************
%% ----- Input Fixed Variables -----
% *************************************************************************
   %SPLN     =   32.716;          % (m^2) or 352.16 ft^2
   %TAU      =   0.22;            % Orbiter slenderness ratio
   ALLE      =   72.4;            % Leading Edge Sweep Angle
   DIA_NOSE  =   0.378;           % or 1.24 ft
   LTD       =   2.48;            % Length to Diameter Ratio
   WID       =   0.13;            % Wing Thickness to Diameter Ratio
% -------------------------------------------------------------------------
% -------------------------------------------------------------------------

  ALLE     =   degtorad(ALLE);

 %% Volume total
    VTOTAL     =    TAU*SPLN^(1.5);

% Calculating Vtot expression in terms of fuselage diameter DIA_FUSE

% 1. Hemi-sphere at nose
    V1       =    (pi/12)*DIA_NOSE^3;     %Vol.Sphere/2

% % 2. Blunted half-cone
%       V2       =    (pi/48)*tan(ALLE)*DIA_FUSE^3   - 0.0112;   %Vol of larger cone - Vol of small cone with DIA_NOSE (fixed)
%
% % 3. Half-Cylinder
%       V3       =    (pi/8)*(DIA_FUSE^3)*(LTD - tan(ALLE)/2) ;
%
% % 4. Wings (as right triangles where length = half-cyll4inder)
%       V4       =    (LTD^2)*WID*(DIA_FUSE^3)/tan(ALLE);

    Const    =     V1 - 0.0112;
    Var      =    (pi/48)*tan(ALLE) + (pi/8)*(LTD - tan(ALLE)/2) + (LTD^2)*WID/tan(ALLE);

    DIA_FUSE         =    ((VTOTAL-Const)/Var)^(1/3);

%  diameter error check
%      if Var =0
%          error('error in calculating diamter')
%      end

%% Calculating Vehicle Length and Span
   AL = DIA_FUSE*LTD;
```

```
    BPLN = 2*AL/tan(ALLE);
    AR = BPLN^2\SPLN;

%% Calculating SWET, Wetted Area
    A1      =   (pi/2)*(DIA_NOSE^2);
    A2      =   (pi*(DIA_FUSE^2))/(2*cos(ALLE)) - (pi*(DIA_NOSE^2))/(2*cos(ALLE));
    A3      =   pi*DIA_FUSE*(AL - (DIA_FUSE/2)*tan(ALLE))+ (pi/8)*(DIA_FUSE^2) ;
    A4      =   (BPLN-DIA_FUSE)*(AL - (DIA_FUSE/2)*tan(ALLE));

    SWET = A1 + A2 + A3 + A4 + SPLN ;

    %Volume Check
    V2      =   (pi/48)*tan(ALLE)*DIA_FUSE^3   - 0.0112;
    V3      =   (pi/8)*(DIA_FUSE^3)*(LTD - tan(ALLE)/2) ;
    V4      =   (LTD^2)*WID*(DIA_FUSE^3)/tan(ALLE);

    VTOTAL = V1+V2+V3+V4;

  % Calculating SFSPLN
     SF = (pi/2)*(DIA_FUSE/2)^2;  %% Recheck ??
     SFSPLN=SF/(SPLN);

 % Kw, Size Fineness Ratio
     AKW        =   SWET/SPLN;
     AKW0       = -93.831*TAU^3 + 58.920*TAU^2 - 5.648*TAU + 2.821;

 % Kv, Size Fineness Ratio (Hypersonic Convergence pg 84 eq 43 Wing Body _typo
     tau_inv =   1/TAU;
     KV      =   0.52734 - 1.1714*10^-3*tau_inv + 5.4888*10^-4*tau_inv^2 - 8.2046*10^-5*tau_inv^3;
   DB = DIA_FUSE;
   SPLN_HT = SPLN*68/352;
   SPLN_VT = SPLN*63/352;
```

### *B.1.2 Geometry Calculation: Generic Lifting Body Configuration using Hypersonic Convergence Relations*

This method uses paramteric equations for several lifting body cross-section profiles as derived in the Hypersonic Convergence. Each shape is iterated by the ‘switch‘ function thus providing a modular method to iterate on distinct geometry shapes.

```
% Geometry Hypersonic convergence shapes for a fixed sweep
% Author: Loveneesh

%% OUTPUTS
% AKW    Ratio of wetted surface area to planform area
% AL   m Vehicle length
% ALLE   radians Sweep angle of the leading edge
% AR      ASPECT RATIO
% BA_BASE      Ratio of base width to height (e)
% BPLN   m Span of the vehicle
% CS_SPAT    Ratio of spatula width to span of vehicle without spatula
% CSPAT m Span of the spatula
% DB   m Body Diameter
% SF        m^2    Frontal Area
```

```
% SFSPLN         Ratio of frotal area to planform area
% SPLN_HT m^2    Horizontal Tail planform area
% SPLN_VT m^2    Vertical Tail planform area
% SWET       m^2    Wetted surface area
% TAU            KüchemannŠs tau
% VTOTAL  m^3    Volume of total vehicle

%% Global Inputs: SPLN
% Local Inputs: E (= b/a), ALLE(=78), CS(ratio c/s)
ALLE = 78;
ALLE = degtorad(ALLE);

%E = BA_BASE; %BA_BASE is given from input file

%% TAU and AKW relations below are based on base shapes for ALLE =78
% Select a base-area shape with the GEO_C counter from input file
SET = GEO_C; %1 to 7

switch SET
case 1
% set=1 Ellipse
%TAU = 0.4826.*E ;  % 0.0483 < TAU < 0.483, 0.1 < E < 1
BA_BASE = TAU/0.4826;
AKW = 2.404.*TAU.^2 + 2.920.*TAU + 2.174;
KS = 0.2413; %(= 0.2413 for elliptical) & (=0.154 for triangular)
case 2
% set=2 half-ellipse
%TAU = 0.2413.*E ;  % 0.0241 < TAU < 0.241, 0.1 < E < 1
BA_BASE = TAU/0.2413;
AKW = 2.226 + 2.917*BA_BASE + 4.689*BA_BASE.^2;
KS = 0.2413; %(= 0.2413 for elliptical) & (=0.154 for triangular)
case 3
% set=3 diamond
%TAU = 0.3074.*E ;  % 0.0307< TAU < 0.307, 0.1 < E < 1
BA_BASE = TAU/0.3074;
AKW = 2.173 + 1.872*TAU + 8.023*TAU.^2;
KS = 0.154; %(= 0.2413 for elliptical) & (=0.154 for triangular)
case 4
% set=4 half-diamond
%TAU = 0.154.*E ;  % 0.0154< TAU < 0.154,  0.1 < E < 1
BA_BASE = TAU/0.154;
AKW = 2.226 + 1.865*TAU + 15.387*TAU.^2;
KS = 0.154; %(= 0.2413 for elliptical) & (=0.154 for triangular)
case 5
% set=5 Blunted Cone (E=Rn/Rb)
%TAU = 0.3048*E.^2 + 0.01875*E  + 0.04826;  % 0.4826< TAU < 0.52
p = [0.3048 0.01875 (0.04826-TAU)];
p1= roots(p);
BA_BASE = p1(p1>=0);
AKW = 4.6*BA_BASE.^2 - 2.350*BA_BASE + 4.111;
KS = 0.2413; %(= 0.2413 for elliptical) & (=0.154 for triangular)
case 6
% set=6  Blunted Half Cone (E=Rn/Rb)
%TAU = 0.1381*E.^2 + 0.01643*E  + 0.2409;  % 0.2409< TAU < 0.258
p = [0.1381 0.01643 (0.2409-TAU)];
p1= roots(p);
```

```
BA_BASE = p1(p1>=0);
AKW = 58.592*BA_BASE.^2 - 25.775*BA_BASE + 5.970;
KS = 0.2413; %(= 0.2413 for elliptical) & (=0.154 for triangular)
 case 7
% set=7  Trapezoid
BA_BASE = 1; %(Can be 1, 1.5, 2)
 if BA_BASE == 1
AKW = 2.906 - 2.022*TAU + 15.706*TAU.^2;
 elseif BA_BASE == 1.5
AKW = 3.013 + 0.706*TAU + 5.438*TAU.^2;
 elseif BA_BASE == 2
AKW = 3.093 + 1.064*TAU + 3.093*TAU.^2;
end
KS = 0.154; %(= 0.2413 for elliptical) & (=0.154 for triangular)
end

%% From here onwards the spatular addition is used from Coleman's Thesis Method
% CS = 0 is the regular shape without spatular advantage.
AKW =  AKW.*(1 + (CS*KS./(1+CS)));
AL = sqrt(SPLN.*tan(ALLE)./(1+CS));

S = AL./tan(ALLE);
CSPAT = S.*CS;
BPLN = 2*S + CSPAT;
CS_SPAT = CS;
DB = BPLN;

SWET = AKW.*SPLN;
SF = pi*BA_BASE.*(S.^2) + BA_BASE.*S.*CSPAT;
SFSPLN = SF./SPLN;

AR = (BPLN.^2)\SPLN;
TAU = TAU;
SPLN_HT = 0.07*SPLN;
SPLN_VT = 0.07*SPLN;

VTOTAL = TAU.*(SPLN.^1.5);

%% This section implements checks on vehicle dimensions.
% VTOTAL >  ENGVOL
% VTOTAL

%ENGINE_NAME :HM7B  VINCI RL10A-1   RL10A-4-1 RL10C-1 RL60  LE-5B2  CE-7.5  CE-20 YF-75 YF-75D  RD-0146 S5.92 S5.80
%ENGSELECT    : 1   2       3         4       5     6     7     8     9     10     11      12      13      14
%Inputs : ENGSELECT, ANENG

%i= ENGSELECT;
%ENGINE_NAME ={'HM7B  VINCI'   'RL10A-1'  'RL10A-4-1'  'RL10C-1'  'RL60'   'LE-5B2'   'CE-7.5'   'CE-20'  'YF-75'  'YF-75D'   'RD-0146'  'S5.92'  'S5.80'};
%ENGLENGTH = [2.1 4.2 1.73  2.3 2.22  2.25  2.8 2.14  2.2 2.8 2.8 2.2 1.03  1.2];
%ENGDIA = [0.99 2.15  0.9 1.53  1.44  2.2 4 1.56  1.5 1.5 1.5 1.2 0.84 2.1];

%ENGLENGTH = ENGLENGTH(i);
%ENGDIA = ENGDIA(i);
```

```

%ENGVOL = ANENG.*ENGLENGTH.*ENGDIA.*ENGDIA; %Volume occupied by engine is taken as a cuboid
```

### B.1.3 Geometry Calculation: Generic OpenVSP Geometry Method

This method shows an example of how OpenVSP geometry modeling software was used to analyze various lifting-body and wing-body geometries. First step was to create models in the OpenVSP, which were then converted into data structure. A MATLAB script was then coded to interpolate among geometry parameters. The code below is an example of such MATLAB script. The interpolating variables were changed according to the vehicle geometry shape as required by the code.

```

% Geometry Hypersonic convergence shapes for variable sweep from VSP
% Author: James Haley

%% OUTPUTS
% AKW    Ratio of wetted surface area to planform area
% AL  m Vehicle length
% ALLE  radians Sweep angle of the leading edge
% AR     ASPECT RATIO
% BPLN  m Span of the vehicle
% CS_SPAT    Ratio of spatula width to span of vehicle without spatula
% CSPAT m Span of the spatula
% DB  m Body Diameter
% SF        m^2    Frontal Area
% SFSPLN        Ratio of frotal area to planform area
% SPLN_HT m^2    Horizontal Tail planform area
% SPLN_VT m^2    Vertical Tail planform area
% SWET       m^2    Wetted surface area
% TAU             KüchemannŠs tau
% VTOTAL   m^3    Volume of total vehicle

%% Global Inputs: SPLN
% Local Inputs: E (= b/a), ALLE(=78), CS(ratio c/s)

ALLE = 78; %must be integer between 65 and 80
E = BA_BASE;

% Select a base-area shape with the SET variable
SET = GEO_C; %1 to 5

switch SET
case 1
% set=1 Rounded Ellipse
%set the nose radius (nr) to eliminate a parameter
nr = 0.1;
%load in the data structure
bcone = load('roundedellipse.mat');
bcone = bcone.results;

%round to nearest 0.03 in nr to fit tabular data
```

```
nr = round(nr/0.05625)*0.05625;

%filter geometry set based on leading edge
bcone = bcone(bcone(:,2)==ALLE,:);

%filter geometry to the nearest nose radius to base diameter ratio
bcone = bcone(bcone(:,3)==nr,:);

%filter geometry to the nearest eccentricty
bcone = bcone(bcone(:,4)==E,:);

%interpolate between planform values
TAU = interp1(bcone(:,7),bcone(:,5),SPLN); % interpolate to the selected planform and select those values
VTOTAL = interp1(bcone(:,7),bcone(:,6),SPLN);
SWET = interp1(bcone(:,7),bcone(:,7),SPLN);
BPLN = interp1(bcone(:,7),bcone(:,8),SPLN);
SF = interp1(bcone(:,7),bcone(:,9),SPLN);
SFSPLN = SF/SPLN;
AR = BPLN^2/SPLN;
AL = (BPLN/2 - nr*BPLN)/tan((90-ALLE)*pi/180) + nr*BPLN;
AKW = SWET/SPLN;

case 2
% set=2 Rounded half-ellipse
%set the nose radius (nr) to elimate a parameter (rounds to nearest table
%increment
nr = 0.1;

%load in the data structure
bcone = load('roundedhalfellipse.mat');
bcone = bcone.results;

%round to nearest 0.1125 in nr to fit tabular data
nr = round(nr/0.1125)*0.1125;

%filter geometry set based on leading edge
bcone = bcone(bcone(:,2)==ALLE,:);

%filter geometry to the nearest nose radius to base diameter ratio
bcone = bcone(bcone(:,3)==nr,:);

%filter geometry to the nearest eccentricty
bcone = bcone(bcone(:,4)==E,:);

%interpolate between planform values
TAU = interp1(bcone(:,7),bcone(:,5),SPLN); % interpolate to the selected planform and select those values
VTOTAL = interp1(bcone(:,7),bcone(:,6),SPLN);
SWET = interp1(bcone(:,7),bcone(:,7),SPLN);
BPLN = interp1(bcone(:,7),bcone(:,8),SPLN);
SF = interp1(bcone(:,7),bcone(:,9),SPLN);
SFSPLN = SF/SPLN;
AR = BPLN^2/SPLN;
AL = (BPLN/2 - nr*BPLN)/tan((90-ALLE)*pi/180) + nr*BPLN;
AKW = SWET/SPLN;

case 3
```

```
% set=3 trapizoid
%set the nose radius (nr) to elimate a parameter (rounds to nearest table
%increment
nr = 0.1;
e = 0.5;

%load in the data structure
bcone = load('trapizoid.mat');
bcone = bcone.results;

%round to nearest 0.1125 in nr to fit tabular data
nr = round(nr/0.1125)*0.1125;

%filter geometry set based on leading edge
bcone = bcone(bcone(:,2)==ALLE,:);

%filter geometry to the nearest nose radius to base diameter ratio
bcone = bcone(bcone(:,3)==nr,:);

%filter geometry to the nearest eccentricty ( base to width ratio )
bcone = bcone(bcone(:,4)==e,:);

%filter geometry to the nearest keystone length ratio of trapizoid ( 0 to 1 )
bcone = bcone(bcone(:,5)==E,:);

%interpolate between planform values
TAU = interp1(bcone(:,7),bcone(:,6),SPLN);  % interpolate to the selected planform and select those values
VTOTAL = interp1(bcone(:,7),bcone(:,7),SPLN);
SWET = interp1(bcone(:,7),bcone(:,8),SPLN);
BPLN = interp1(bcone(:,7),bcone(:,9),SPLN);
SF = interp1(bcone(:,7),bcone(:,10),SPLN);
SFSPLN = SF/SPLN;
AR = BPLN^2/SPLN;
AL = (BPLN/2 - nr*BPLN)/tan((90-ALLE)*pi/180) + nr*BPLN;
AKW = SWET/SPLN;

case 4
% set=4 rounded cone
bcone = load('roundedcone.mat');
bcone = bcone.results;

E = E/2;
%round to nearest 0.03 in E to fit tabular data
E = round(E/0.03)*0.03;

%filter geometry set based on leading edge
bcone = bcone(bcone(:,2)==ALLE,:);
%filter geometry to the nearest nose radius to base diameter ratio
bcone = bcone(bcone(:,3)==E,:);
%interpolate between planform values
TAU = interp1(bcone(:,7),bcone(:,4),SPLN);  % interpolate to the selected planform and select those values
VTOTAL = interp1(bcone(:,7),bcone(:,5),SPLN);
SWET = interp1(bcone(:,7),bcone(:,6),SPLN);
BPLN = interp1(bcone(:,7),bcone(:,1),SPLN);
```

```
SF = interp1(bcone(:,7),bcone(:,8),SPLN);
SFSPLN = SF/SPLN;
AR = BPLN^2/SPLN;
AL = (BPLN/2 - E*BPLN)/tan((90-ALLE)*pi/180) + E*BPLN;
AKW = SWET/SPLN;

 case 5
% set=5 half rounded Cone

bcone = load('halfroundedcone.mat');
bcone = bcone.results;

E = E/2;
%round to nearest 0.03 in E to fit tabular data
E = round(E/0.03)*0.03;

%filter geometry set based on leading edge
bcone = bcone(bcone(:,2)==ALLE,:);
%filter geometry to the nearest nose radius to base diameter ratio
bcone = bcone(bcone(:,3)==E,:);
%interpolate between planform values
TAU = interp1(bcone(:,7),bcone(:,4),SPLN);  % interpolate to the selected planform and select those values
VTOTAL = interp1(bcone(:,7),bcone(:,5),SPLN);
SWET = interp1(bcone(:,7),bcone(:,6),SPLN);
BPLN = interp1(bcone(:,7),bcone(:,1),SPLN);
SF = interp1(bcone(:,7),bcone(:,8),SPLN);
SFSPLN = SF/SPLN;
AR = BPLN^2/SPLN;
AL = (BPLN/2 - E*BPLN)/tan((90-ALLE)*pi/180) + E*BPLN;
AKW = SWET/SPLN;


end
ALLE = ALLE*pi/180;

SPLN_HT = 0.07*SPLN; %RANDOM FOR NOW
SPLN_VT = 0.07*SPLN;

% FURTHER VARIABLES REQUIRED  FOR OUTPUT
% DB Body diameter
% SPLN_HT
% SPLN_VT
% SPLN_W
```

## B.2 Aerodynamic Methods

The aerodynamic analysis method is based on empirical correlations of the data generated initially at the McDonnel Douglas Company during the HyFAC studies[**?** ] and is modified here from the original plots provided by Coleman[**?** ].

### B.2.1 Subsonic Aerodynamic Analysis

```
% Aerodynamics Analysis of Wing Body Reentry Vehicles in SubSonic Range (M: 0 - 0.8)
```

```
% Source: HYFAC(Phase-I,Vol-2, Part-II, pg 4.16 onwards)/Hyp Conv
% Author: Loveneesh

%%%%%%%% Pre-Allocate Outputs %%%%%%%%
ALDMAX=zeros(size(AMACH));
ALIND=zeros(size(AMACH));
CD0=zeros(size(AMACH));
CLA=zeros(size(AMACH));
CL=zeros(size(AMACH));
CD=zeros(size(AMACH));

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

ALIND(AMACH <= 0.8)=0.45;   %from fig4-19
ALDMAX(AMACH <= 0.8)= sqrt(pi.*(ECDF/4).*((BPLN.^2)./SWET));   % eq on fig 4-13, ECDF from the plot = 280
CD0(AMACH <= 0.8)=1./(4.*ALIND(AMACH <= 0.8).*ALDMAX(AMACH <= 0.8).^2);
%CLA(AMACH <= 0.8)=0.024;    %from fig 4-19, alternate analytical equation used instead as shown in next step
CLA(AMACH <= 0.8)=2*pi.*AR./(57.3*(2 + sqrt(4 + ((AR./cos(ALLE/2)).^2) - (AR.*AMACH(AMACH <= 0.8)).^2))); %from HYFAC Ref-1 (Barnard Spencer)
CL = CLA.*AOA;
CD = CD0 + ALIND.*CL.^2;

ALD = CL./CD;
```

### B.2.2 Supersonic Aerodynamic Analysis

```
  %%%%%%%% Pre-Allocate Outputs %%%%%%%%
  ALDMAX=zeros(size(AMACH));
   ALIND=zeros(size(AMACH));
  CD0=zeros(size(AMACH));
  CLA=zeros(size(AMACH));
  CL=zeros(size(AMACH));
  CD=zeros(size(AMACH));

    %%%%%% Regression Data %%%%%%%%
AMACH_MAP=[1.5, 2.0, 4.5,5.0,6.0, 12.0,18.0,24.0,30.0];
TAU_MAP=[0.0111, 0.0185, 0.027, 0.0364, 0.0468, 0.058, 0.07, 0.0828, 0.0962, 0.1103, 0.125, 0.1402, 0.1561, 0.1726, 0.1895, 0.207, 0.225, 0.2435, 0.2625, 0.2819, 0.3018, 0.3222, 0.343, 0.3642, 0.3858, 0.4078, 0.4303];

ALDMAX_MAP=[8.829, 8.351, 7.799, 7.181, 6.612, 6.183, 5.817, 5.457, 5.121, 4.824, 4.531, 4.239, 3.974, 3.721, 3.465, 3.22, 2.98, 2.735, 2.49, 2.254, 2.02, 1.78, 1.535, 1.286, 1.031, 0.771, 0.507;
 8.708, 8.145, 7.582, 7.019, 6.527, 6.154, 5.787, 5.418, 5.096, 4.759, 4.466, 4.19, 3.934, 3.655, 3.416, 3.186, 2.967, 2.7, 2.504, 2.283, 2.126, 1.956, 1.773, 1.63, 1.476, 1.36, 1.192;
 8.676, 8.148, 7.621, 7.093, 6.582, 6.178, 5.8, 5.446, 5.118, 4.804, 4.517, 4.244, 3.974, 3.704, 3.441, 3.193, 2.958, 2.708, 2.465, 2.228, 1.996, 1.763, 1.531, 1.298, 1.066, 0.833, 0.601;
 8.682, 8.059, 7.436, 6.915, 6.487, 6.053, 5.65, 5.322, 4.982, 4.682, 4.414, 4.16, 3.886, 3.657, 3.397, 3.152, 2.924, 2.703, 2.521, 2.338, 2.143, 1.968, 1.816,
```

```
    1.674,  1.523,  1.39, 1.257;
7.842,  7.407,  6.973,  6.539,  6.109,  5.704,  5.346,  5.032,
    4.719,  4.455,  4.184,  3.926,  3.693,  3.432,  3.208,
    2.982,  2.753,  2.551,  2.331,  2.126,  1.932,  1.738,
    1.544,  1.35, 1.156,  0.962,  0.768;
5.674,  5.43, 5.154,  4.845,  4.53, 4.261,  4.025,  3.825,
    3.608,  3.416,  3.24, 3.046,  2.872,  2.705,  2.555,  2.405,
      2.277,  2.12, 1.988,  1.864,  1.726,  1.601,  1.476,
    1.345,  1.252,  1.131,  1.067;
5.669,  5.43, 5.154,  4.845,  4.53, 4.261,  4.021,  3.785,
    3.576,  3.391,  3.205,  3.016,  2.852,  2.705,  2.555,
    2.405,  2.26, 2.12, 1.98, 1.847,  1.719,  1.588,  1.455,
    1.318,  1.179,  1.038,  0.893;
5.669,  5.43, 5.154,  4.845,  4.53, 4.261,  4.021,  3.785,
    3.576,  3.391,  3.205,  3.016,  2.852,  2.705,  2.555,
    2.405,  2.26, 2.12, 1.98, 1.847,  1.719,  1.588,  1.455,
    1.318,  1.179,  1.038,  0.893;
5.669,  5.43, 5.154,  4.845,  4.53, 4.261,  4.021,  3.785,
    3.576,  3.391,  3.205,  3.016,  2.852,  2.705,  2.555,
    2.405,  2.26, 2.12, 1.98, 1.847,  1.719,  1.588,  1.455,
    1.318,  1.179,  1.038,  0.893];


%      %%%%%%%% Subsonic  Analysis %%%%%%%%
  SWET = AKW*SPLN;
  ALDMAXS = sqrt(pi.*(ECDF/4).*((BPLN.^2)./SWET));
  ALINDS = 0.45;
  CD0S = 1./(4.*ALINDS.*ALDMAXS.^2);

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

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

  %%%%%%%% Left  side  of  M1.2  Analysis %%%%%%%% Same  for  WB and
     AB
    CD0(AMACH >= 0.80 & AMACH < 1.2) = CD0S + DCDT_MAX./0.4.*(
    AMACH(AMACH >= 0.80 & AMACH < 1.2)-0.8); % linear  Drag  rise
    Y = Y0 + m(x-x0)
    ALDMAX(AMACH >= 0.80 & AMACH < 1.2)=0.5.*sqrt(1./(ALINDS.*
    CD0(AMACH >= 0.80 & AMACH < 1.2))); % (L/D)_max = sqrt(cd0/K
    ')  Approximation

    %%%%%%%% Right  side  of  M1.2  Analysis %%%%%%%% Same  for  AB
    and WB
    CD_2M=1/(4*interp2(TAU_MAP,AMACH_MAP,ALDMAX_MAP,TAU,2.0,'
    spline').^2*ALINDS);
    CD_12M=CD0S+DCDT_MAX;
    CD0(AMACH >= 1.2 & AMACH <= 2.0)=(CD_2M-CD_12M)./0.8.*(AMACH
    (AMACH >= 1.2 & AMACH <= 2.0)-1.2)+CD_12M; % linear  Drag
    function  Y = Y0 + m(x-x0)  from  M1.2  to  M2
    ALDMAX(AMACH >= 1.2 & AMACH <= 2.0)=0.5.*sqrt(1./(CD0(AMACH
    >= 1.2 & AMACH <= 2.0)*ALINDS));

    %%%%%%%% Analysis %%%%%%%%
    % CLA(AMACH >= 0.80 & AMACH < 1.5)=(0.022-0.02)./(1.5-0.8)
```

```
     .*(AMACH(AMACH >= 0.80 & AMACH < 1.5)-0.8)+0.020; %Gary (WB)
    CLA(AMACH >= 0.80 & AMACH < 1.2)= 0.0052.*AMACH(AMACH >=
     0.80 & AMACH < 1.2) + 0.0202;                          %Linear
     relation from excel file

    %%%%%%%% Analysis %%%%%%%%
  %CLA(AMACH >= 1.5 & AMACH <= 2.0)=0.03./AMACH(AMACH >= 1.5 &
    AMACH <= 2.0).^0.75+0.00025;     %Gary (WB)
  %CLA(AMACH >= 1.2 & AMACH <= 2.0)=0.0098.*AMACH(AMACH >= 1.2 &
      AMACH <= 2.0) + 0.0379;          %Linear relation from excel
     file
    CLA(AMACH >= 1.2 & AMACH <= 2.0)=0.0112.*(AMACH(AMACH >= 1.2
      & AMACH <= 2.0).^2) - 0.0452.*AMACH(AMACH >= 1.2 & AMACH <=
      2.0) + 0.0657;   %Polynomial relation from excel file,
     updates by Loveneesh Fig4-19 data
  %ALIND(AMACH >= 0.8 & AMACH <= 2.0) = 0.47;  %Approx Value
  ALIND(AMACH >= 0.8 & AMACH <= 2.0)= 0.0651.*(AMACH(AMACH >=
     0.8 & AMACH <= 2.0).^2) - 0.0758.*AMACH(AMACH >= 0.8 & AMACH
      <= 2.0) + 0.4083; %Polynomial expression from excel file
  CL = CLA.*AOA;
  CD = CD0 + ALIND.*CL.^2;
  ALD = CL./CD;
```

### B.2.3 Hypersonic Aerodynamic Analysis

```
    %%%%%%%% Pre-Allocate Outputs %%%%%%%%
    ALDMAX=zeros(size(AMACH));
    ALIND=zeros(size(AMACH));
    CD0=zeros(size(AMACH));
    CLA=zeros(size(AMACH));

    %%%%%% Regression Data %%%%%%%%%
AMACH_MAP=[1.5, 2.0, 4.5,5.0,6.0, 12.0,18.0,24,30];
TAU_MAP=[0.0111, 0.0185, 0.027, 0.0364, 0.0468, 0.058, 0.07,
     0.0828, 0.0962, 0.1103, 0.125, 0.1402, 0.1561, 0.1726,
     0.1895, 0.207, 0.225, 0.2435, 0.2625, 0.2819, 0.3018,
     0.3222, 0.343, 0.3642, 0.3858, 0.4078, 0.4303];

ALDMAX_MAP=[8.829, 8.351, 7.799, 7.181, 6.612, 6.183,
     5.817, 5.457, 5.121, 4.824, 4.531, 4.239, 3.974,
     3.721, 3.465, 3.22, 2.98, 2.735, 2.49, 2.254, 2.02,
     1.78, 1.535, 1.286, 1.031, 0.771, 0.507;
 8.708, 8.145, 7.582, 7.019, 6.527, 6.154, 5.787, 5.418,
     5.096, 4.759, 4.466, 4.19, 3.934, 3.655, 3.416, 3.186,
       2.967, 2.7, 2.504, 2.283, 2.126, 1.956, 1.773,
     1.63, 1.476, 1.36, 1.192;
 8.676, 8.148, 7.621, 7.093, 6.582, 6.178, 5.8, 5.446,
     5.118, 4.804, 4.517, 4.244, 3.974, 3.704, 3.441,
     3.193, 2.958, 2.708, 2.465, 2.228, 1.996, 1.763,
     1.531, 1.298, 1.066, 0.833, 0.601;
 8.682, 8.059, 7.436, 6.915, 6.487, 6.053, 5.65, 5.322,
     4.982, 4.682, 4.414, 4.16, 3.886, 3.657, 3.397, 3.152,
       2.924, 2.703, 2.521, 2.338, 2.143, 1.968, 1.816,
     1.674, 1.523, 1.39, 1.257;
 7.842, 7.407, 6.973, 6.539, 6.109, 5.704, 5.346, 5.032,
     4.719, 4.455, 4.184, 3.926, 3.693, 3.432, 3.208,
     2.982, 2.753, 2.551, 2.331, 2.126, 1.932, 1.738,
     1.544, 1.35, 1.156, 0.962, 0.768;
 5.674, 5.43, 5.154, 4.845, 4.53, 4.261, 4.025, 3.825,
     3.608, 3.416, 3.24, 3.046, 2.872, 2.705, 2.555, 2.405,
       2.277, 2.12, 1.988, 1.864, 1.726, 1.601, 1.476,
```

```
    1.345,  1.252,  1.131,  1.067;
5.669,  5.43, 5.154,  4.845,  4.53, 4.261,  4.021,  3.785,
    3.576,  3.391,  3.205,  3.016,  2.852,  2.705,  2.555,
    2.405,  2.26, 2.12, 1.98, 1.847,  1.719,  1.588,  1.455,
    1.318,  1.179,  1.038,  0.893;
5.669,  5.43, 5.154,  4.845,  4.53, 4.261,  4.021,  3.785,
    3.576,  3.391,  3.205,  3.016,  2.852,  2.705,  2.555,
    2.405,  2.26, 2.12, 1.98, 1.847,  1.719,  1.588,  1.455,
    1.318,  1.179,  1.038,  0.893;
5.669,  5.43, 5.154,  4.845,  4.53, 4.261,  4.021,  3.785,
    3.576,  3.391,  3.205,  3.016,  2.852,  2.705,  2.555,
    2.405,  2.26, 2.12, 1.98, 1.847,  1.719,  1.588,  1.455,
    1.318,  1.179,  1.038,  0.893];



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

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

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

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

  CL = CLA.*AOA;
  CD = CD0 + ALIND.*CL.^2;
  ALD = CL\CD;
```

## B.3 Propulsion Method

Liquid rocket propulsion analysis using pre-existing engines characteristics. The analysis then modulates the thrust availability as per the user input.

```

%Engine Selection
%Variable ENGSELECT used to select an engine

%ENGINE_NAME  :HM7B   VINCI  RL10A-1     RL10A-4-1  RL10C-1  RL60   LE-5
     B2   CE-7.5   CE-20  YF-75  YF-75D   RD-0146  S5.92  S5.80
%ENGSELECT     :  1   2        3           4        5     6     7     8     9     10
     11       12       13       14

%% PRE-ALLOCATE OUTPUTS
AISP                = zeros(size(THRL_VAR));
FT_AVAIL            = zeros(size(THRL_VAR));
CFN                 = zeros(size(THRL_VAR));
```

```
OF                  = zeros(size(THRL_VAR));
ISP_ISPAVAIL        = zeros(size(THRL_VAR));

%% ENGINE SELECTION PARAMETER
i                   = ENGSELECT;

%% ENGINE DATA
ENGINE_NAME ={'HM7B VINCI'  'RL10A-1' 'RL10A-4-1' 'RL10C-1' '
      RL60'  'LE-5B2'  'CE-7.5'  'CE-20' 'YF-75' 'YF-75D'  'RD
      -0146' 'S5.92' 'S5.80' 'XX-NO-NAME'};
AE_AT          = [83.1 240 40  84  130 80  110 80  100 80  80  210
      153 153];
AEXIT          = [0.769  3.629 0.636 1.838 1.627776  3.7994  12.56
      1.910376  1.76625 1.76625 1.76625 1.22 0.553896 3.46185];
AISP_REF       = [445  465 410 451 450 465 447 454 443 438 442 451
      327 302];
ALT_REF        = [100e3  100e3 100e3 100e3 100e3 100e3 100e3 100e3
      100e3 100e3 100e3 100e3 100e3 100e3];
GAMMA_RKT      = [1.25 1.25  1.25  1.25  1.25  1.25  1.25  1.25
      1.25  1.25  1.25  1.25  1.25  1.25 ];
OF_RKT         = [5.14 5.8 5 5.5 5.5 6 5 5.05  5 5.2 6 6 2 1.8];
PC_RKT         = [3599996.2  6000000.4 2400004.2 3899999.3
      4356975.0 8257987.5 3769290.0 5990334.0 526890.0  3678097.5
      4099609.5 7899297.0 9700004.4 880000.0];
% PE_RKT = [0.01  0.01  0.01  0.01  0.01  0.01  0.01  0.01  0.01
        0.01  0.01  0.01  0.01  0.01];
% PE_RKT solved for using equation 3-25 in sutton ed 8 and using
       PC given
% above
PE_RKT         =
      [2376.80705909996,1007.39893688627,4116.90131624602,2539.10488810242,1611.23819518581,5728.17565368216,1730.0

THRUST_REF   = [62000  180000  68000 99000 101000  250000  150000
        73500 200000  785000  88000 98000 19610 2950];
WENG           = [165  550 131 168 190 498 290 435 588 550 550 243
      75  310];
ENGLENGTH    = [2.1  4.2 1.73  2.3 2.22  2.25  2.8 2.14  2.2 2.8
      2.8 2.2 1.03  1.2];
ENGDIA         = [0.99 2.15  0.9 1.53  1.44  2.2 4 1.56  1.5 1.5
      1.5 1.2 0.84 2.1];
OXIDISER   = {'LO2'  'LO2' 'LO2' 'LO2' 'LO2' 'LO2' 'LO2' 'LO2' '
      LO2' 'LO2' 'LO2' 'LO2' 'N2O4'  'N2O4'};
RHO_OX         = [1141 1141  1141  1141  1141  1141  1141  1141
      1141  1141  1141  1141  1442  1442];
FUEL           = {'LH2'  'LH2' 'LH2' 'LH2' 'LH2' 'LH2' 'LH2' 'LH2'
      'LH2' 'LH2' 'LH2' 'LH2' 'UDMH'  'UDMH'};
RHO_FUEL       = [66 66  66  66  66  66  66  66  66  66  66  66
      791 791];

%% ALLOCATE VALUES BASED ON ENGINE SELECTED
ENGINE_NAME = ENGINE_NAME{i};
AE_AT          = AE_AT(i);
AEXIT          = AEXIT(i);
AISP_REF       = AISP_REF(i);
ALT_REF        = ALT_REF(i);
GAMMA_RKT      = GAMMA_RKT(i);
OF_RKT         = OF_RKT(i);
PC_RKT         = PC_RKT(i);
PE_RKT         = PE_RKT(i);
THRUST_REF   = THRUST_REF(i);

```

```
ENGLENGTH     = ENGLENGTH(i);
ENGDIA        = ENGDIA(i);
WENG          = WENG(i)*9.81;
ENGVOL        = ANENG.*ENGLENGTH.*ENGDIA.*ENGDIA; %Volume occupied by engine is taken as a cube

OXIDISER      = OXIDISER{i};
RHO_OX        = RHO_OX(i);
FUEL          = FUEL{i};
RHO_FUEL      = RHO_FUEL(i);

    %% Rubber Engine Regression data
    OF_S = ...
   [5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5;
    6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6;
    7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7];
    FT_FTAVAIL_S = ...
   [0.198 0.205 0.214 0.227 0.237 0.249 0.260 0.271 0.285 0.304 0.332 0.371 0.405 0.436 0.464 0.507 0.548 0.598 0.649 0.694 0.746 0.787 0.822 0.851 0.879 0.914 0.951 0.985 0.999 1.000;
    0.198 0.205 0.214 0.227 0.237 0.249 0.260 0.271 0.285 0.304 0.332 0.371 0.405 0.436 0.464 0.507 0.548 0.598 0.649 0.694 0.746 0.787 0.822 0.851 0.879 0.914 0.951 0.985 0.999 1.000;
    0.198 0.205 0.214 0.227 0.237 0.249 0.260 0.271 0.285 0.304 0.332 0.371 0.405 0.436 0.464 0.507 0.548 0.598 0.649 0.694 0.746 0.787 0.822 0.851 0.879 0.914 0.951 0.985 0.999 1.000];

    ISP_ISPAVAIL_S = ...
   [0.9845  0.9867  0.9867  0.9867  0.9867  0.9889  0.9889  0.9889  0.9889  0.9911  0.9911  0.9933  0.9933  0.9956  0.9956  0.9956  0.9978  0.9978  0.9978  0.9978  0.9978  0.9978  0.9978  0.9978  0.9978  0.9978  1.0000  1.0000  1.0000  1.0000;
    0.9756  0.9756  0.9761  0.9778  0.9778  0.9778  0.9787  0.9798  0.9800  0.9804  0.9827  0.9844  0.9855  0.9867  0.9889  0.9892  0.9911  0.9927  0.9933  0.9942  0.9956  0.9956  0.9978  0.9978  0.9978  0.9978  0.9988  1.0000  1.0000  1.0000;
    0.9662  0.9662  0.9662  0.9679  0.9685  0.9697  0.9707  0.9709  0.9720  0.9738  0.9755  0.9797  0.9805  0.9820  0.9842  0.9863  0.9873  0.9887  0.9910  0.9920  0.9932  0.9943  0.9955  0.9955  0.9966  0.9977  0.9978  0.9986  0.9999  1.0000];

    %% Atmospheric condition - Reference Pressure - Design Point
  FLTCOND          = fltcon(ALT_REF,0,0,0); % Assumed sea level condition?
  PREF             = FLTCOND.P;

    %% Compute Thrust at Max Power
    % Break Up CF into parts
    AA = ((2.*GAMMA_RKT.^2)./(GAMMA_RKT-1)) .* ((2./(GAMMA_RKT+1)).^((GAMMA_RKT+1)./(GAMMA_RKT-1)));
    BB = 1-((PE_RKT./PC_RKT).^((GAMMA_RKT-1)./(GAMMA_RKT)));

    % Compute CF
    CFN              = sqrt(AA .* BB) + ((PE_RKT-P)./(PC_RKT)) .* AE_AT;
```

```
    CFN_REF          = sqrt(AA .* BB) + ((PE_RKT-PREF)./(PC_RKT))
      .* AE_AT;
    CFN_VAC          = sqrt(AA .* BB) + ((PE_RKT-0)./(PC_RKT)) .*
      AE_AT;

    % Compute Thrust Available
    FT_AVAIL         = ANENG.*(CFN./CFN_REF).*THRUST_REF; % All
     vector points will = max thrust

    %% Compute Isp at Max Power
  CSTAR              = AISP_REF.*Go./CFN_REF;
  AISP_VAC           = CSTAR.*CFN_VAC./Go;
  AISP               = AISP_VAC-(CSTAR./Go).*(P./PC_RKT).*AE_AT;

  %% Assign Values to O/F, Thrust, and Isp Zero Matrix
    OF(THRL_VAR >= 0.198 & THRL_VAR <= 1.0)              = OF_RKT
     ; % Assign O/F_rkt to O/F range where Variable thrust
     setting is 19.8% to 100%, Outside of this range = 0 bc 0
     vector
    FT_AVAIL(THRL_VAR < 0.198 & THRL_VAR > 1.0)          = 0; %
     Set Thrust Available, outside of variable thrust range, = 0,
       all others still = max thrust
    AISP(THRL_VAR < 0.198 & THRL_VAR > 1.0)              = 0; %
     Set Isp, outside of variable thrust range, = 0, otherwise it
       is the same value everywhere
    ISP_ISPAVAIL(THRL_VAR >= 0.198 & THRL_VAR <= 1.0)    =
     interp2(FT_FTAVAIL_S,OF_S,ISP_ISPAVAIL_S,THRL_VAR(THRL_VAR
     >= 0.198 & THRL_VAR <= 1.0),OF(THRL_VAR >= 0.198 & THRL_VAR
     <= 1.0),'spline'); % Assign Isp varriable values (
     percentages) to locations of thrust generation

    %% True Isp and Thrust available at variable thrust settings
      (Each is a matrix/Vector, for use conisder as a thrust /
     isp lookup table)
    FT_AVAIL         = FT_AVAIL.*THRL_VAR; % Scale max thrust to
     variable thrust values at each location of thrust output
    AISP             = AISP.*ISP_ISPAVAIL; % Scale max Isp to
     variable Isp values at each location of thrust output
  %Rocket Engine
  %DUCT_PRESSURE = 0;
```

## B.4 Weights and Volume Budget Estimates

Weight and volume budget calculation is a modified form of the VDK weights method.[**?** ] Since the propulsion system is not sized, this method takes weight and volume of preselected engine from propulsion module.

```
  %Author: Loveneesh
  %VDK Weights Paramteric Method modified for Fixed Engine
     weight and Volume

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

```

```
%ENGINE_NAME :HM7B VINCI RL10A-1 RL10A-4-1 RL10C-1 RL60 LE-5B2 CE-7.5 CE-20 YF-75 YF-75D RD-0146 S5.92 S5.80
%ENGSELECT : 1 2 3 4 5 6 7 8 9 10 11 12 13 14
i= ENGSELECT;
%Engine Performance Deck
ENGINE_NAME ={'HM7B VINCI' 'RL10A-1' 'RL10A-4-1' 'RL10C-1' 'RL60' 'LE-5B2' 'CE-7.5' 'CE-20' 'YF-75' 'YF-75D' 'RD-0146' 'S5.92' 'S5.80'};
AE_AT = [83.1 240 40 84 130 80 110 80 100 80 80 210 153 153];
AEXIT = [0.769 3.629 0.636 1.838 1.627776 3.7994 12.56 1.910376 1.76625 1.76625 1.76625 1.22 0.553896 3.46185];
WENG = [165 550 131 168 190 498 290 435 588 550 550 243 75 310];
ENGLENGTH = [2.1 4.2 1.73 2.3 2.22 2.25 2.8 2.14 2.2 2.8 2.8 2.2 1.03 1.2];
ENGDIA = [0.99 2.15 0.9 1.53 1.44 2.2 4 1.56 1.5 1.5 1.5 1.2 0.84 2.1];

OXIDISER ={'LO2' 'LO2' 'LO2' 'LO2' 'LO2' 'LO2' 'LO2' 'LO2' 'LO2' 'LO2' 'LO2' 'LO2' 'N2O4' 'N2O4'};
RHO_OX = [1141 1141 1141 1141 1141 1141 1141 1141 1141 1141 1141 1141 1442 1442]; %in kg/m^3
FUEL ={'LH2' 'LH2' 'LH2' 'LH2' 'LH2' 'LH2' 'LH2' 'LH2' 'LH2' 'LH2' 'LH2' 'LH2' 'UDMH' 'UDMH'};
RHO_FUEL = [66 66 66 66 66 66 66 66 66 66 66 66 791 791];

ENGINE_NAME = ENGINE_NAME{i};
AE_AT = AE_AT(i);
AEXIT = AEXIT(i);
ENGLENGTH = ENGLENGTH(i);
ENGDIA = ENGDIA(i);
WENG = WENG(i)*9.81;

OXIDISER = OXIDISER{i};
RHO_OX = RHO_OX(i);
FUEL = FUEL{i};
RHO_FUEL = RHO_FUEL(i);


%********************************************************************************
%% WEIGHT BUDGET OWE
WOX_WF = (1-1/WR)/FF - 1;
RHO_PPL=(WOX_WF+1)/(WOX_WF/RHO_OX + 1/RHO_FUEL);

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

WOPER=85.0*ANCREW+FWPPRV*ANPAX;

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

WP = WENG*ANENG; %N

% WEIGHT BUDGET OWE=WSTR+WSYS+WOP+WCREW
```

```
OEW_W = (1+AMUA)*(WP + WFIX + WOPER)/(1 - (1+AMUA)*(AKSTR*SPLN^0.138 + FWSYS));
OWE_W = OEW_W + WPAY + WCREW;

% *******************************************************************************
%% VOLUME BUDGET OWE

VTOTAL = TAU*SPLN^1.5;

VFIX = VUN + AKVMND*ANCREW;
VSYS = VFIX + AKVS*VTOTAL;
VPAY = ANPAX*AKVPAX + (WCARGO/RHO_CARGO/9.81);
VENG = ANENG*(((AEXIT + (AEXIT/AE_AT)))/2)*ENGLENGTH*0.7; %0.7 assumes that 70% englength is inside the vehicle
VCREW = (AKVCPRV+AKVCREW)*ANCREW;
VVOID = VTOTAL*AKVV;

OWE_V = (VTOTAL - VSYS - VPAY - VENG - VCREW - VVOID)/((WR-1)/RHO_PPL/9.81);
AIP = RHO_PPL/(WR-1);

% *******************************************************************************
%% WEIGHT AND VOLUME BREAKFORWN

OWE = OWE_W;
OEW = OEW_W;

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

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

VP = VENG;
VPPL = WPPL/RHO_PPL/9.81;
VFUEL = WFUEL/RHO_FUEL/9.81;
VOX = WOX/RHO_FUEL/9.81;
```