FENIX HYPERSONICS	SENIOR DESIGN: MAE 4151 Project	Ref.: MAE 4351-001-2021 Date: 14. May. 2022 Name: Roman Renazco Status: Semi-Complete

Design of Commercial Hypersonic Aircraft Based on Sänger II (Weight & Balances Lead and Synthesis)

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Summary:

This report introduces hypersonics and presents a project/business venture focused on high-speed air travel. A team of 15 senior-level aerospace engineering students under the moniker of Fenix Hypersonics have taken on the task of designing an aircraft to achieve the similar objectives as Sänger II. The requirements are as follows; commercial transport for passenger, Mach 5 boost-glide, and HOTOL among others. This report is written by the project's Weight & Balance discipline lead and Synthesis member. Fenix Hypersonics was split into 9 separate disciplines, each pertaining to a specific realm of aircraft design, each member of the team is a part of two disciplines. Parametric Sizing was achieved using Hypersonic Convergence. A solution space was successfully created in the Parametric Sizing phase. The Configuration Layout phase was fully developed and automated. Finally, the Configuration Evaluation phase yielded optimal vehicle designs for an airbreathing and rocket variant with PAX 36 Tau 0.11 and PAX 44 Tau 0.09 respectively. The larger focus of this project was to gain a greater understanding of multi-disciplinary design in how interconnected each discipline is in aircraft design and the benefits in optimizing the "teamwork" of each part of an aircraft rather than individually optimized.

Distribution:

Institution:	Dept.:	Name:
The University of Texas at Arlington	MAE	Dr. Bernd Chudoba

Work Disclosure Statement

The work I performed to document the results presented in this report was performed by me, or it is otherwise acknowledged.

Date: 5/14/2022

Signature:

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Nomenclature [1] [2]

b	span
c	spatular width
c/s	spatula ratio, spatula width to outboard semispan
C_{D0}	zero-lift drag coefficient
C_{ev}	expansion component velocity coefficient
C_{ea}	expansion angularity coefficient
$(C_f/2\ A_w/A_3)_c$	dimensionless boundary-layer skin-friction quantity
$(C_f\ A_w/A_3)_b$	burner effective drag coefficient
$C_{L\alpha}$	lift curve slope
C_{Lmax}	maximum lift coefficient
C_{pe}	expansion specific heat
f	fuel-to-air ratio
h	vehicle height
h_c/l_c	ratio of external compression height to length
h_{iso}/l_{iso}	ratio of isolator height to length
h_{pr}	fuel heating value
I_{sp}	specific impulse
I_{str}	structural index, ratio of structural weight to wetted area
K_{str}	structural weight shape factor
l	vehicle length
L'	induced drag coefficient
L/D	Lift-to-Drag ratio
L_{comb}	length of combustor
l_c/l_w	ratio of external compression length to total vehicle length
N_{rkt}	number of rocket motors
S_{front}	frontal area
S_{pln}	planform area
S_{wet}	wetted area
t_{cruise}	cruise endurance time
T_{rkt}	total thrust from rocket motor
V_{fx}/V_3	ratio of fuel velocity to axial flow velocity
V_f/V_3	ratio of fuel velocity to total flow velocity
V_{ppl}	propellant volume
V_{prop}	propulsion system volume
V_{sys}	systems volume
V_{total}	total volume
V_{void}	void volume
W/S	wing loading
W_{margin}	design weight margin
W_{ppl}	propellant weight
W_{prop}	total propulsion system weight
W_{str}	structural weight
W_{sys}	systems weight

Parameters for Code and Equations for Weight Estimation

AAISLE	Area for transverse aisles from center to center of outboard bays, ft^2
ABSEAT	Seat area for business class passengers, ft^2
ACABIN	Passenger cabin floor area, ft^2
ACLSET	Area for each closet including half of an aisle, ft^2
AEWT	Weight of alternate engines, lb
AFSEAT	Seat area for first class passengers, ft^2

AGALLY	Area for each galley inchided half of an aisle, ft^2
ALAVA	Area for each lavatory included half of an aisle, ft^2
ALTEWT	Weight-to-thrust ratio per engine for the alternate propulsion system, lb
ALTTHR	Rated thrust per engine for the alternate propulsion system, lb
AR	Wing aspect ratio
arctan	Arctangent function
ARVT	Vertical tail theoretical aspect ratio
ASEAT	Area per seat, ft^2
ASEATS	Area for passengers, ft^2
ASERVS	Area for passenger services, ft^2
ASW	Average sweep angle weighted by distance from the centerline, deg.
ATSEAT	Seat area for tourist class passengers, ft
AWASTE	Area of the cabin that is wasted due to the slanted side wall, ft^2
B	Wing span, ft
BA	Factor used in the detailed wing weight estimation method
BATWT	Storage system density for the alternate energy source, lb/energy.
BAYW	Passenger bay width, ft
BMAi	Local required bending material
BPP	Weight of baggage per passenger, lb
BT	Wing equivalent bending factor
BTB	Wing equivalent bending material factor without the sweep angle adjustment
BTE	Wing inertia relief factor due to engines
C4	Factor used in the calculation of the wing sweep aeroelastic factor.
C6	Factor used in the calculation of the wing sweep aeroelastic factor.
CARBAS	Carrier based aircraft switch
CARGF	Cargo aircraft floor factor
CARGOF	Cargo other than passenger baggage carried in fuselage, lb
CARGOW	Cargo carried in wing, lb
CAYA	Factor used in wing sweep and aeroelastie tailoring factor
CAYE	Propulsion system pod inertia relief factor
CAYF	Multiple fuselage factor
CAYL	Wing sweep factor including aeroelastic tailoring
Ci	Local chord length, ft. Used in the detailed wing weight estimation method.
CSVT	Factor used for vertical tail weight calculation
CSWi	Secant of the load path sweep angle
DAV	Average fuselage diameter, ft
DELMEi	Local moment of the pressure load used for the engine inertia relief calculation
DELMi	Local moment of the pressure load used in wing weight estimation method
DELPi	Local pressure load used in wing weight estimation
DELTA	Atmospheric pressure ratio, cruise altitude to pressure at sea level
DESRNG	Design range, nmi
DF	Maximum fuselage depth, ft
DFTE	Aircraft type
DG	Design gross weight, lb
DGW	Design gross weight input variable
DIH	Wing dihedral angle, deg
DNAC	Average diameter of the scaled engine nacelles, ft
DY	Y-distance from current to previous integration station, ft
EEM	Factor used in the detailed wing weight estimation method.
EETA	Engine position factor, ft
EEXP	Engine weight scaling parameter
EINL	Engine inlet weight scaling exponent
ELi	Partial summation, tip to the current integration station of the p-load along the load path, psi

ELtot	Total pressure load along the load path
EMi	Partial summation of EMtot
EMS	Wing strut bracing factor
EMtot	Total wing bending moment modified by the local load path sweep angle
ENOZ	Engine nozzle weight scaling exponent
ETAi	Local wing station location, ft
FAERT	Aeroelastic tailoring factor used in the design of the wing
FCOMP	Composite utilization factor for wing structure
FIXSPN	Fixed wing span, ft
FLAPR	Ratio of total movable wing surface area (flaps, elevators, spoilers,etc.) to wing area.
FMXTOT	Aircraft maximum fuel capacity, lb
FNAC	Average diameter of each scaled engine, ft
FNEF	Number of fuselage mounted engines, scaled to account for distributed propulsion if applicable
FNENG	Total number of engines, scaled to account for distributed propulsion if applicable
FNEW	Number of wing mounted engines, scaled to account for distributed propulsion if applicable
FPAREA	Fuselage planform area
FPART	Passenger compartment length for the first class passengers, in.
FPITCH	Seat: pitch for the first class passengers, in
FSTRT	Wing strut bracing factor
FSWREF	Reference wing area for FUELRF, ft^2
FTHRST	Rated thrust of each scaled engine, scaled for distributed propulsion if applicable, lb
FTHRUST	Rated thrust of each scaled engine, scaled for distributed propulsion if applicable, lb
FUELM	Total aircraft fuel weight, lb
FUELRF	Fuel capacity of wing at reference area FSWREF, lb
FUFU	Maximum fuel capacity of the fuselage, lb
FULAUX	Auxiliary (external) fuel tank capacity, lb
FULDEN	Fuel density ratio for alternate fuels compared to jet fuel
FULFMX	Total fuel capacity of the fuselage, 1b. Includes wing carry through structure and fuselage tanks.
FULWMX	Total fuel capacity of the wing, lb
FUSCLA	User specified factor A for the 1.5 power term. Used to seale wing fuel capacity.
FUSCLB	User specified factor B for the linear term. Used to scale wing fuel capacity.
FUSMLT	Factor used in calculation of fuselage passenger compartment length.
FWMAX	Factor for wing fuel capacity equation
GLOV	Total glove and bat area beyond theoretical wing area, ft^2
GW	Ramp weight, lb
HFac	Horizontal tail geometric factor
HHT	Horizontal tail mounting location indicator
HTVC	Modified horizontal tail volume coefficient.
HYDPR	Hydraulic system pressure, psi. The default value is 3,000.
IEW	1.0 for wing mounted engines and 0.0 for fuselage mounted engines
IVSWP	Variable sweep indicator with 1.0 for variable sweep wing and 0.0 for fixed wing
Lh	Horizontal tail moment arm, ft
Lv	Vertical tail moment arm, ft
Mac	Mean aerodynamic chord, ft
max(x.y)	Function that returns larger of x and y parameters
NABR	Number of seats abreast
NAISL	Number of aisles
NBAY	Number of passenger bays
NCEN	Factor used in calculation of fuselage length.
NCLSET	Number of closets
NCON	Number of cargo containers
NDOORS	Number of doors in the passenger compartment.
NEALT	Number of engines for the alternate propulsion system

NEF	Number of fuselage mounted engines
NENG	Total number of engines
NEW	Number of wing mounted engines
NFABR	Number of first class passengers abreast,
NFIN	Number of fins
NFLCR	Number of flight crew.
NFUSE	Number of fuselages
NGALC	Number of galley crew
NGALLY	Number of galleys
NLAVA	Number of lavatories
NP	Number of passengers in a given class
NPB	Number of business class passengers
NPF	Number of first class passengers
NPT	Number of tourist class passengers
NR	Number of rows in a passenger class
NSTU	Number of flight attendants
NTABR	Number of tourist class passengers abreast.
NTANK	Number of fuel tanks
NVERT	Number of vertical tails
OSSPAN	Outboard wing semispan of HWB aircraft, ft
OWFURN	Weight of the furnishings group, 1b. Used in alternate operating empty weight method.
OWSYS	Total systems and equipment weight, 1b. Used in alternate operating empty weight method.
OWWE	Aircraft empty weight, 1b. Used in alternate operating empty weight method.
PASS	Total number of passengers
PCTL	Fraction of load carried by the defined wing
Pi	Local load intensity factor, ranging from 0.0 to 1.0
PITCH	Seat pitch, in
PM yr	Total area moments along the wing load path used in the detailed wing weight estimation method
POWMAX	Storage system capacity for alternate energy source, energy, must be consistent with BATWT.
POWWT	System weight for alternate propulsion system, 1b
QCRUS	Cruise dynamic pressure, psf
QDIVE	Dive maneuver dynamic pressure, psf
RFACT	Supersonic cruise factor. Equal to 0.00004 for subsonic cruise, 0.00009 for supersonic cruise.
RSPCHD	Percent chord of the HWB fuselage rear spar at the fuselage centerline.
RSPCHD	Percent chord of the HWB fuselage rear spar at the fuselage centerline
RSPSOB	Percent chord of the HWB fuselage rear spar at the side of body
SA	Sine of the average wing sweep angle weighted by distance from the centerline
SAFTB	Area of the aft body, ft
SCAN	Canard theoretical area, ft^2
SFIN	Fin theoretical area, ft^2
SFLAP	Total movable wing surface area including flaps, elevators, spoilers, etc., ft^2
sHT	Horizontal tail theoretical area, ft^2
SLAM	Sine of the 3/4 chord wing sweep angle
SPAN	Wing span, ft
SPWCON	Constant weight term used in the alternate operating empty weight method, 1b
SPWGW	Multiplier for gross weight used in the alternate operating empty weight method, lb/lb
SPWSW	Multiplier for wing area used in the alternate operating empty weight method, lb/ft^2
SPWTH	Multiplier for thrust per engine used in the alternate operating empty weight method, 1b/lb
Stot	Total wing areas along the wing load path used in the detailed wing weight estimation method
svT	Vertical tail theoretical area per tail, ft^2
sw	Reference wing area, ft^2
SWEEP	Quarter chord sweep angle of the wing, deg
SWFUS	Fuselage wetted area ft^2

SWIFU	Wetted area of fuselage, ft^2
SWIVT	Wetted area of vertical tail, ft^2
SWP	Wing load path sweep angle, deg
SWPLE	Sweep angle of the passenger cabin, deg
SWPVT	Vertical tail sweep angle at 25% chord, deg
SWTCN	Wetted area of canards, ft^2
SWTHT	Wetted area of horizontal tail, ft^2
SWTNA	Wetted area of nacelles, ft^2
SWTWG	Wetted area of wings, ft^2
SX	Wing trapezoidal area, ft^2
TanLE	Tangent of the cabin leading edge sweep angle, estimated using
TAXOFL	Fixed taxi out fuel, 1b
TAXOTM	Taxi out time, min
TCA	Weighted average of the wing thickness to chord ratio
TCHT	Horizontal tail thickness to chord ratio
TCVT	Vertical tail thickness to chord ratio
THEXF	Aircraft excess fuel capacity, 1b
THRSO	Rated thrust of each baseline engine, 1b
THRUST	Rated thrust of each sealed engine, 1b
Ti	Local thickness to chord ratio used in the detailed wing weight estimation method
TLAM	Tangent of the 3/4 chord wing sweep angle
TNAC	Total number of nacelles plus 0.5 if there is a center-mounted engine
TPART	Passenger compartment length for the tourist class passengers, in.
TPITCH	Seat pitch for tourist class passengers, in
TR	Taper ratio of the wing
TRAFTB	Taper ratio of the aft body
TRCAN	Canard theoretical taper ratio
TRFIN	Fin theoretical taper ratio
TRHT	Horizontal tail theoretical taper ratio
TRVT	Vertical tail theoretical taper ratio
TXFUFL	Taxi fuel flow, 1b/hr /engine
ULE	Structural ultimate load factor
VARSWP	Wing variable sweep weight penalty factor
VCMN	Cruise Mach number
VFac	Vertical tail geometric factor.
VFACT	Variable wing sweep factor
Vh	Horizontal tail volume coefficient
VMAX	Maximum Mach number
VTVC	Modified vertical tail volume coefficient
Vv	Vertical tail volume coefficient
WAC	Weight of the air conditioning system group, 1b
WAI	Weight of the anti-icing system for transport aircraft, 1b
WAISL	Width of the aisle, in
WAPU	Weight of the auxiliary power unit, 1b
WARM	Weight of the armament group, 1b (Includes thermal protection system, armor, fixed weapons)
WAVONC	Weight of the avionics system group, 1b
WCAN	Canard weight, lb
WCARGO	Weight of cargo that will be placed in containers, 1b
WCON	Weight of cargo containers, 1b
WEC	Weight of the engine controls system, lb
WELEC	Weight of the electrical system group, lb
WENG	Weight of each scaled baseline engine, 1b
WENGB	Weight of baseline engine, 15. Includes inlet and nozzle weight

WENGP	Intermediate variable used in the calculation of the weight of each engine, lb.
WF	Maximum fuselage width, ft
WFAISL	First class aisle width, in
WFIN	Fin weight, 1b
WFLCRB	Weight of flight crew and baggage, 1b
WFSYS	Weight of the fuel system (including tanks and plumbing), 1b
WFURN	Weight of the furnishings group, 1b
WFURNB	Weight of the furnishings group without additional 1% of the empty weight, lb
WFUSE	Fuselage weight, 1b
WHT	Horizontal tail weight, 1b
WHYD	Weight of the hydraulic system group, 1b
WIDTHF	Fuselage width parameter based on the first class
WIDTHT	Fuselage width parameter based on the tourist class
WIN	Weight of the instruments system group, lb
WINL	Weight of the engine inlet, 1b
WINLB	Inlet weight for baseline engines, lb
WLDG	Aircraft design landing weight, 1b
WLG	Total landing gear weight, 1b
WLGM	Main landing gear weight, 1b
WLGN	Nose landing gear weight, lb
WMARG	Empty weight margin, 1b
WNAC	Weight of nacelle or air induction system, 1b
WNOZ	Weight of the engine nozzle, 1b
WNOZB	Nozzle weight for baseline engine, 1b
WOIL	Weight of the engine oil, 1b
WOPIT	Total operating items weight, lb
WOWE	Aircraft operating empty weight, lb
WPAINT	Area density of paint for all wetted areas, lb/ ft?
WPASS	Total passenger weight, lb
WPAYLOAD	Aircraft total payload weight, lb
WPBAG	Weight of passenger baggage for transport aircraft
WPMISC	Additional miscellaneous propulsion system weight, 1b
WPMSC	Weight of miscellaneous propulsion systems such as engine controls, starter, and electrical, 1b
WPOD	Weight of engine pod including the nacelle, 1b
WPPASS	Weight per passenger, 1b
WPRO	Total aircraft propulsion group weight, Id
WSC	Weight of the surface control systems, 1b
WSR	Required wing loading, lb/ ft?
WSRV	Weight of passenger service for transport aircraft, 1b
WSTART	Weight of the engine starter system, lb
WSTRCT	Total aircraft structural group weight, 1b
WSTUAB	Weight of flight attendants and galley crew and baggage, Ib
WSYS	Total aircraft systems and equipment group weight, 1b
WSYSB	Total aircraft systems and equipment group weight without additional 1% of the empty weight, 1b
WTAISL	Width of the tourist class aisles, in
WTBAT	Weight of alternate energy source storage system, lb
WTHR	Weight of the thrust reversers, lb
WTNFA	Total weight of engine pod(s) not including the nacelle, lb
WTPNT	Weight of aircraft paint, 1b
WUF	Weight of unusable fuel, 1b
WVT	Vertical tail weight, 1b
WWE	Aircraft empty weight, lb
WWING	Wing weight, 1b

WZF	Aircraft zero fuel weight, lb
XL	Total fuselage length, ft
XLP	Length of passenger compartment, ft
XLPB	Passenger compartment length without additional length needed for doors, ft
XLW	Fixed length of side wall, ft
XMLG	Length of the extended main landing gear oleo, in.
XNAC	Average length of the scaled engine nacelles, ft.
XNLG	Length of the extended nose landing gear oleo, in.
YEE	Location of outboard on wing engine, measured from centerline, in
Yi	Y-location of the integration station location used in the detailed wing weight estimation method, ft

GREEK SYMBOLS

γ_c compression system ratio of specific heats
γ_e expansion system ratio of specific heats
η_1 adiabatic compression efficiency
η_b burner efficiency
θ_{1n} first nozzle angle
θ_{2n} second nozzle angle
τ Küchemann's slenderness parameter

ACRONYMS

AVD Aerospace Vehicle Design Laboratory
CE Configuration Evaluation
c.g. center of gravity
CL Configuration Layout
DB Data-Base
DBS Data-Base System
HL Horizontal Landing
HTO Horizontal Take Off
KB Knowledge-Base
KBS Knowledge-Base System
LaRC Langley Research Center
Li-AL Lithium-Aluminum alloy
M Managerial
MLW Maximum Landing Weight
MSTC Multiple Stages To Cruise
OEW Operating Empty Weight
OWE_w Operating Weight Empty from weight budget
OWE_v Operating Weight Empty from volume budget
PDE Pulse Detonation Engine
PS Parametric Sizing
RBCC Rocket-Based Combined Cycle
RJ Ramjet
RKT Rocket
RSM Response Surface Method
S Synthesis
SiC/SiCMMC Silicon Carbide/Silicon Carbide Metal Matrix Composite
SERN Single Expansion Ramp Nozzle
SJ Scramjet
SSTC Single Stage To Cruise
T Technologies
TBCC Turbine-Based Combined Cycle
T-D Thrust minus Drag
TJ Turbojet
TOGW Take Off Gross Weight
TPS Thermal Protection System
TSTC Two Stage To Cruise
T/W Thrust-to-Weight ratio
VAB Vehicle Analysis Branch
VTO Vertical Take Off

I. Introduction

The faster the better, with the technology finally viable, hypersonic flight will pave the way of the future. This project entails a refreshed look at a generation of space transportation systems of reusable vehicles. With the advent of reusable rockets headed by SpaceX competition for transportation within or near space has become an economic necessity with all previous rocket designs becoming null and void with their one-time-use design. Hypersonic air travel at speeds greater than Mach 5 represent an opportunity for cheaper, more environmentally friendly air travel as well as developing a cheaper avenue for space transportation via reusability in the high altitude and speed achieved by hypersonic vehicles. The transport of goods or people through air travel make up a world-wide revenue of 838 billion U.S. dollars in 2019 alone, this is a massive industry primed to be innovated to achieve more efficient and cheaper air travel. [3] All too often hypersonic research has been geared to military purposes; however, this report will entail a primarily “purely-business” style focusing on producing best design for the highest ROI for a commercial hypersonic aircraft.

Fig. 1 Hyperion Fenix Aircraft [4]

A. Project Scope

The project is a Senior Design Project for the 2nd semester of Senior Design for Aerospace Engineers at the University of Texas at Arlington under Dr. Chudoba. We will be developing a sizing methodology for the 3 initial steps of preliminary aircraft design; Parametric Sizing, Configuration Layout, and Configuration Evaluation of “Sänger III”; a Mach 5 commercial jet. This will have the following assumptions: a range of 3,630 miles, 10 to 50 PAX, Concorde operational characteristics, and TSS certification requirements by European standards.

This will also entail studies into analyzing the market, competition, technology, and cost/benefit assessments to ensure proper trade studies. Team Fenix holds a focus on comparing RBCC vs an all-rocket boost-glide design.

B. Global Context and Applications

This project investigates the creation of a commercially viable hypersonic aircraft for point-to-point and space tourism flights. These comprise of two separate markets ripe for customers such as governments, fractional buyers, international and charter companies. The profit mainly lies in hypersonic or supersonic business jets mainly due to the limited potential demand for business travelers placing a limit on the size of the aircraft; assessing the Concorde, a supersonic business jet, the potential demand for such travel amounts to approximately 37500 passengers per year (resulting in an average of 100 passengers daily) suggesting large hypersonic or supersonic aircraft would be a bad investment due to a lack of demand. [5]

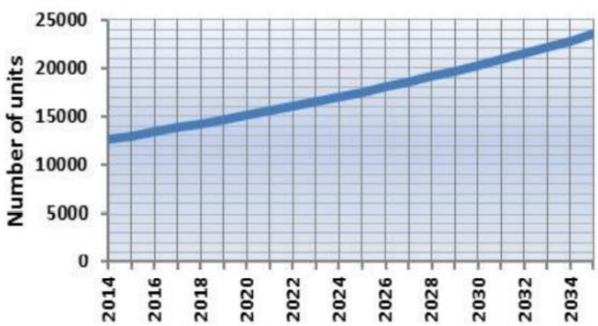


Fig. 2 Business Jet Fleet Growth Forecast [5]

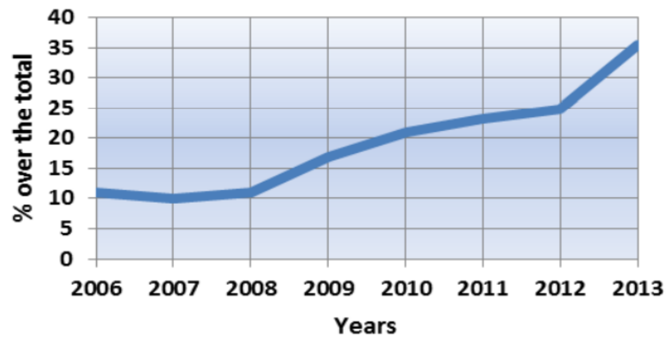


Fig. 3 High-end Business Jet Deliveries over Total Aviation Deliveries [5]

Business jets for passengers and high-end transports are on the rise, slowly encompassing more of the business jet industry; this apparent growth is partly explained by the rise of "Ultra High Net Worth Individuals" or UHNWI with a growth of approximately 5% per year all willing and wanting to purchase high-end business jets that are in the $40 million dollar price range. [5] Despite the seemingly exorbitant cost to the average person, these individuals seldom consider the price as the primary factor for a purchase but rather weighing the internal comfort, maximum range, and speed possible, and the 'cool' factor, this leads to a significantly less elasticity in the high-end business jet market compared to the general line of business jets of which suffered severely in economic crisis. The high-end business jet market will soon be replaced by 2035 with supersonic/hypersonic vehicles given that said vehicles cost no more than 150% the typical price of a high-end business jet, this would be followed by an increased demand of 14500 new business jets and a total demand of 3625 of high-end business jets. [5] This purchasing by UHNWIs and associated entities could be likened to the purchasing of a yacht or super-yacht for prestige and 'showing off' that is often exhibited by the ultra-wealthy. These supersonic/hypersonic business jets would be used for urgent travel and fast cargo for special goods such as live/perishable valuables, express mail, or transcontinental organ transport, all of which cater to the wealthy class of individuals.

The second market possible for this project comprise of suborbital space flights which would use skipping maneuvers to put passengers into temporary 'orbit'. With the advent of the space tourism market taking reservations from various companies such as Virgin, Armadillo, XCOR, and SpaceX a demand for space tourism has been formed with the most attractive markets being in the USA, China, and Europe, unsurprisingly being the locations where the wealthy reside. Overall, the decision making process of the consumer for space tourism weighs the following: [5]

- Safety
- Company reputation
- No-gravity duration
- Uniqueness of experience provided
- Period of training and prep required

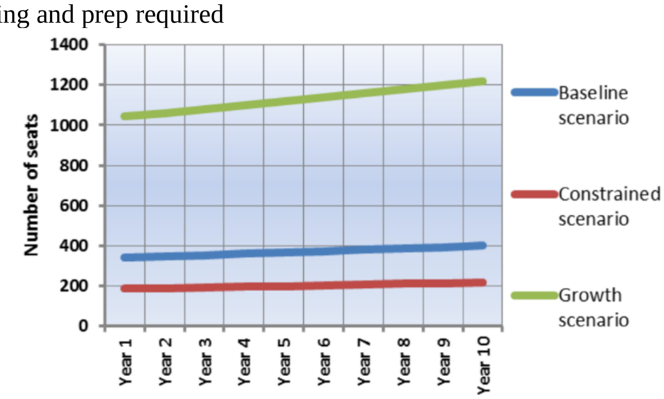


Fig. 4 Space Tourism Projected Demand Growth [5]

Similarly, companies that are well known are perceived to have a greater deal of safety. Seen above is a 10-year forecast of the space tourism market starting in 2015; the blue represents an economic and political situation like today, the red represents an economic crisis leading to less purchasing power by consumers, the green represents a greater investment by public and private entities into the technology required and a positive change in consumer behavior. These predictions are made with a price scenario of $100k to $200k leading to 20% of Americans with a net worth between 25 and 50 million US dollars would be interested.[5]

These two routes for the commercialization of supersonic/hypersonic/sub-orbital transport hold great possibilities for profit and the raising of public and private interest of such travel in the civilian world rather than the primarily defense uses hypersonic and sub-orbital research has been focused on.

C. Historical Background

Timeline

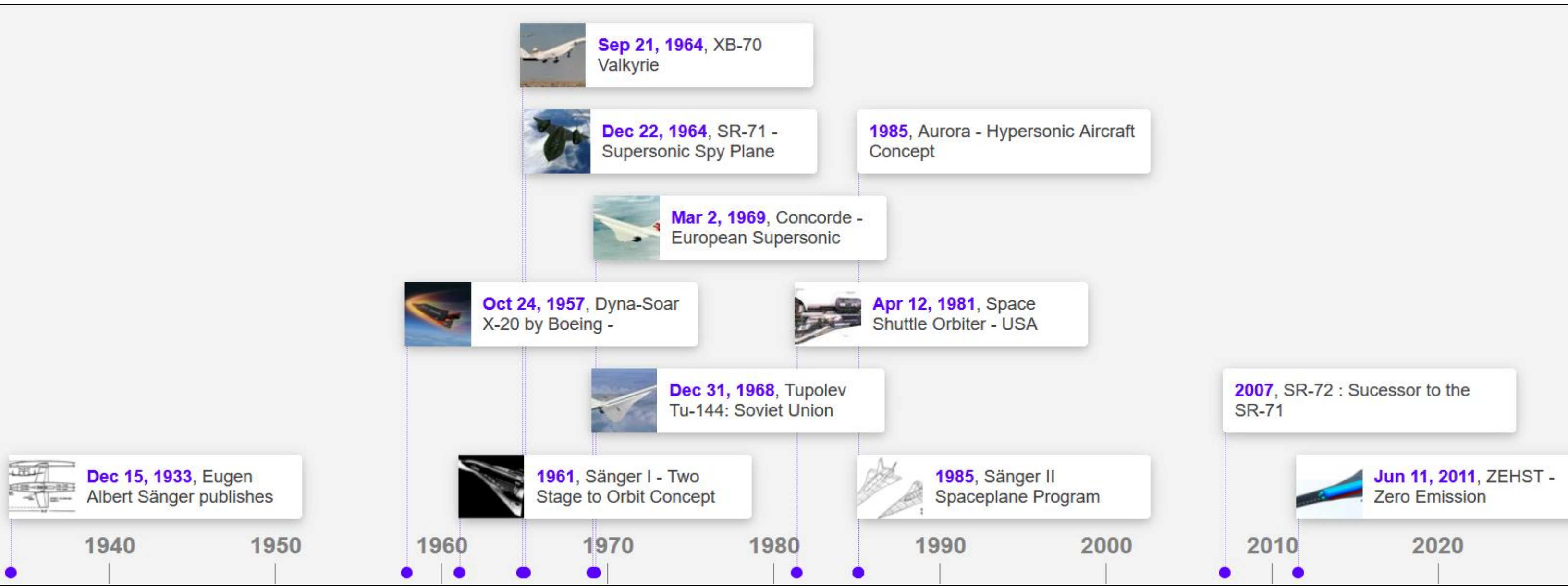


Fig. 5 Historical Timeline

Mr. Sänger – The Birth of Hypersonics in Europe

Hypersonics in Europe began with Eugen Albert Sänger, a German-Austrian rocket pioneer in his publishing of a book, "*Raketenflugtechnik",* also known as "Rocket Flight Engineering" in 1933. [6] This included his design for a hypersonic rocket plane of which could theoretically glide at Mach 13. This was revolutionary and ahead of its time with much of the scientific community still focusing on propellor aircraft. [7] After extensive rejection and consistent work Sänger gained the attention of German high command on the eve of WWII in 1936 with their interest in establishing Sänger a classified aerospace institute to develop his Silverbird, a hypersonic bomber concept; by 1939 Sänger was developing ramjet engines, and the Silverbird lay by the wayside with estimates of 20 years for technology to catch up to be feasible. [6] Once WWII had concluded Sänger refused to work with Russians or Americans, instead settling in France until finally returning to Germany when the country was allowed aerospace research as the head of a new jet propulsion institute in Stuttgart. [6] For the rest of Sänger's life he would continue to lobby for spaceplane designs to be pursued by the German industry, finally being taken up by Messerschmidt-Boelkow-Bloehm (MBB) in 1961 to 1969 resulting in the creation of the Sänger I; a two-stage-to-orbit conceptual space vehicle.[8]

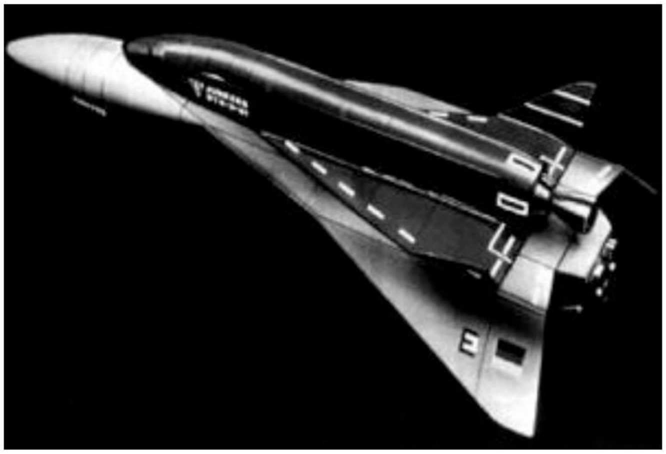


Fig. 6 Sänger I [8]

Come the late 1980s renewed interest in the Sänger program by MBB and other defense companies in Germany led to the birth of the Sänger II program funded by the Germany's new "Hypersonic Technology Program". [9]

Concorde – UK and France joint program on Supersonics

The most ambitious aircraft program conceived in aviation history, previous the Concorde supersonic speed were only for adrenaline-junkie fighter pilots and even then that had only been recently achieved in the 1950s by the F-100 Super Sabre the first fighter to exceed Mach 1 in steady, level flight. [10] The Concorde sought to send over a hundred passengers at over 1,100 miles per hour. The humble beginnings of the Concorde began with the Royal Aircraft Establishment of Britain, at the time being one of the most forefront institutions in supersonic research, set up the Supersonic Transport Aircraft Committee in 1956 (STAC), of which included some of the greatest minds in British aviation from engineers to ministers and business men; the committee organized a set of sub-committees that culminated in the development and reporting of recommendations of two supersonic aircraft designs.

These reports were used to develop concepts for a supersonic transport by the British and French. In the case of the British there was a focus on long-range aircraft supersonic configurations while the French on medium-range configurations, however both were on-board for the concept of slender delta wing planforms for their improved aerodynamic efficiencies at higher Mach numbers (up to Mach 2.2). An immense amount of cooperation between France and Britain began with the nationalized manufactures Sud-Aviation and BAC respectively began in November 1962 once a general agreement on the design and responsibilities between each country was finished. [10]

Primarily, Britain was tasked with the development of the engines and non-wing control surfaces while France was tasked with the development of the fuselage and wings of the craft. Much of the initial development was focused on aerodynamics, materials, and structures which were all immense issues at such high-speed flight, in the meantime the engineering firms were faced in creating preliminary aircraft designs and establishing marketing decisions for potential customers.

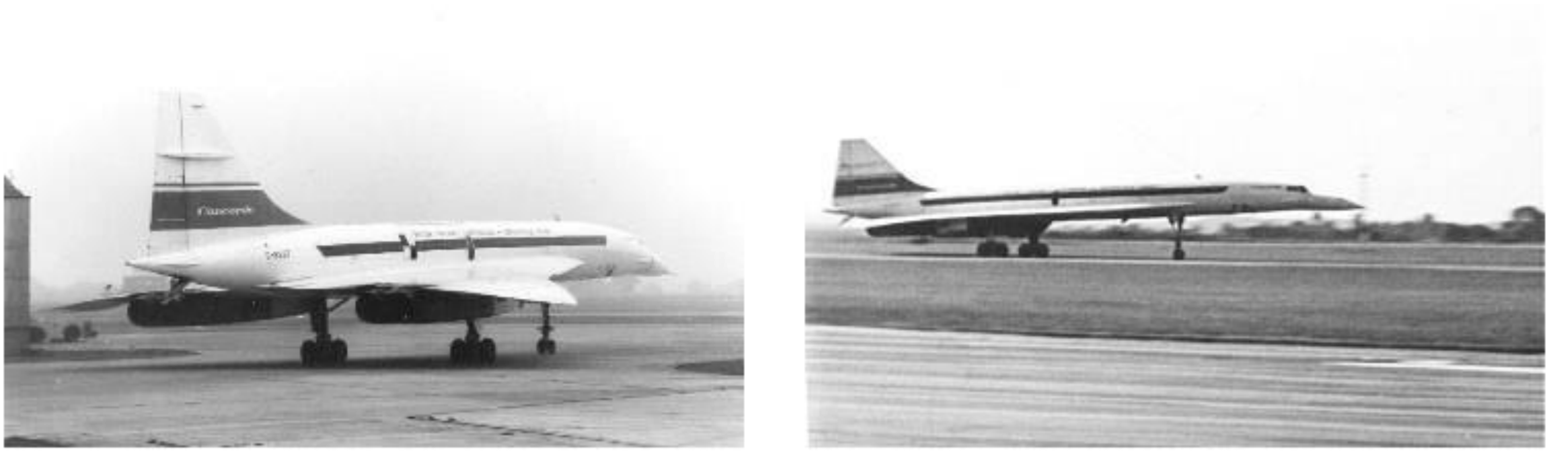


Fig. 7 Prototype Concorde Flight (Concorde/Concord 001) – 1969 [10]

Seen above is the maiden flight of the first prototype of the Concorde, however it would be another 7 years in 1976 when the Concorde would enter mainstream service. A funny fact often touted by each countries engineering teams is how Britain and Concorde worked seamlessly without conflict on all parts of the aircraft's development pardon it's the aircrafts name; the British "Concord" and the French "Concorde" which finally became the "Concorde" for both countries when the above prototype was finally completed in Britain. With 74 preorders for the Concorde by airliners around the world the hopes for the program were high and optimistic.

Fig. 8 Concorde Airliner for British Airways [10]

Finally rolling out to the public in 1976 after years of development, testing, certification around the world passengers were finally cruising at Mach 2 in style with a maximum passenger number of 130 with 2 pilots. The aircraft had a TOGW of 185,000 kg and planform area of 358 m^2.[10] A compendium of more detailed specifications for the Concorde may be seen in Appendix C: Aircraft Database.

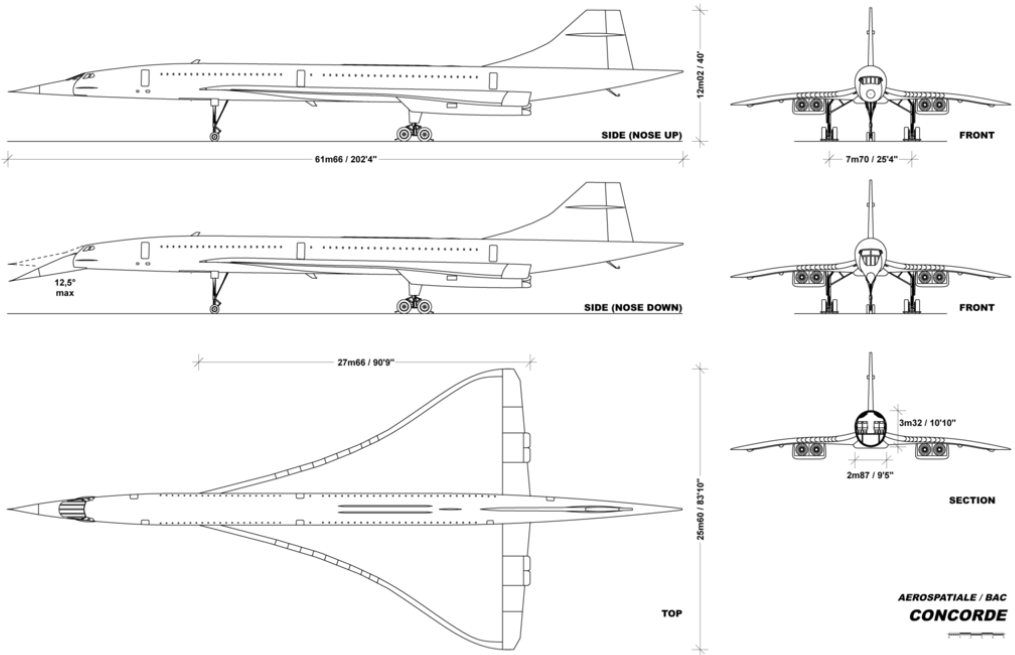


Fig. 9 Concorde Dimensions and Planform Shape [10]

The Concorde had a complex Ogee wing reminiscent of a combination of delta-wings, said wing was optimized precisely for its mission profile and trajectory for maximum cruise range. With a leading-edge sweep starting at 75 degrees and adjusted to 60 degrees the aircraft also had a lower aspect-ratio than typical commercial airliners being closer to that of a jet fighter, likewise for the thrust-to-weight ratio at take-off. Despite the engineering success of the Concorde the aircraft had some issues on the business side of things, being a inexorably loud aircraft due to its design and shock wave creation when reaching breaking the sound barrier the aircraft was severely limited to purely ocean routes for supersonic travel due to government restrictions placed at the behest of public outcry of the noise experienced, this cut severely into the profitability of the Concorde as the main benefit were the fuel savings made at supersonic speeds. Even these factors impinging the Concorde the aircraft was in service for 27 years straight until a severe crash in 2000 in Paris which killed all occupants onboard and many more in a hotel the craft crashed on to until 2001 when limited Concorde flight services were resumed.

Tupolev 144 Series – Russia's Supersonic Transport - *US later joint work*

The Tupolev series began in the Cold War era of the 1960s to have the Easts version of the Concorde program. Evidently there are various rumors the Tupolev 144-D was assembled and designed using stolen plans of the Concorde from U.S.S.R. operatives active in Europe which seems possible due to the stark similarities of the crafts with the Tupolev 144-D seemingly the 'budget version'. The program began in 1962 continuing to 1971 when the first demonstration flight of the Tu-144-D at a Paris airshow. The first passenger flights began late in 1975 a month before Concordes. [11]

Fig. 10 Tu-144 D U.S.S.R. Aircraft [11]

With slight better range and speed performance specifications than the Concorde the Tu-144 series make up the fastest commercial supersonic aircraft to date, however many issues propped up in its rollout and use in requiring immense costs to maintain, fuel and propulsion system problems and multiple crashes. This led to the quick retiring of the program in 1983. [11]

SÄENGER II Program - Hypersonic Flight and Space Transport

The program was intended to address two future challenges of the Europe; Sänger a space transportation system and a hypersonic transport aircraft; this featured two stages, the first comprising of a cruise-capable vehicle utilizing turboramjet engines and the second stage having two variants; the CARGUS and the HORUS. [12]
The rationale for the SÄENGER II program is as follows from a report by Koelle: [13]

- Horizontal Launch feasible
- Cruise capability of 3000 to 4000 km
- Cost reduction of 10- 30 % of the disposable Ariane 5/ Hermes cost per launch
- Limited technology development
- Safe launch and landing conditions

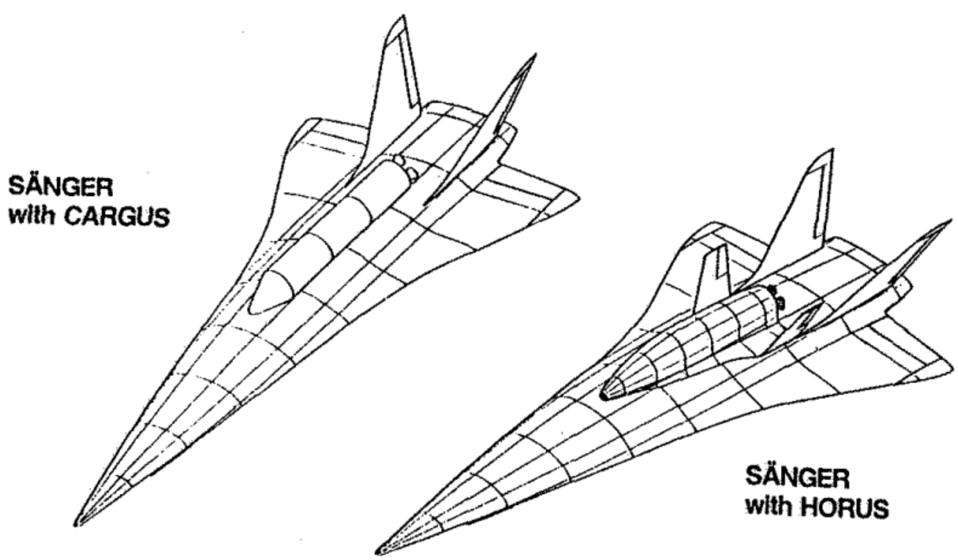


Fig. 11 Sänger hypersonic first stage with CARGUS (left) and HORUS (right) [12]

The CARGUS had the purpose of being an expendable upper stage for LEO payloads while the HORUS had the purpose of being a manned, winged vehicle for space station crew and supply missions, the 1st stage was named EHTV or European Hypersonic Transport Vehicle.

Table 1 EHTV, CARGUS, HORUS Specifications

	EHTV [9]	CARGUS [14]	HORUS [15]
Gross Mass	254,000 kg	62,000 kg	112,000 kg
Empty Mass	156,000 kg	6,000 kg	32,600 kg
Thrust	1,499.995 kN	1050.00 kN	1,280.00 kN
Isp	1,200 sec.	439 sec.	490 sec.
Burn Time	6,565 sec.		298 sec.
Diameter	14 m		5.5 m
Span	41.4 m		15.6 m
Length	84.5 m		27.6 m
Propellant	Air/LH2	Lox/LH2	Lox/LH2
No. Engines	6	1	1
Engine	Co-axial Turboramjet	Vulcan	ATCRE
Cost (1985)	$10 million		$18 million

The Sänger program sought to transport around 230 passengers in business class for a range over 10,000 km at Mach 4.4 at an altitude of 24.5 km as well as a non-passenger version capable of reaching the space station orbit from Europe; cruise and horizontal landing and take-off capability is required for geopolitical reasons in providing Europe with autonomy. [12] The EHTV would be able to convert between a passenger focused aircraft to a launcher-stage aircraft for HORUS (36 passengers) and CARGUS where the cabin in the passenger model would simply be replaced with a fuel tank. [13]

Table 2 EHTV Operations and Lifetime

	Passenger Transport (HST)	Launcher Stage (STS)
Cruise Speed	Mach 0.8/ 4.4	Mach 0.8/ 4.4/ 6.8
Flight Range	10,500 km	2*3500 km
Flight Altitude (max)	24,500 km	31,000 km
Operational Lifetime	15 years 20,000 flights 55,000 hours	25 years 300 – 400 flights 1000 – 1500 hours
Thrust level at take-off	300 kN	350 kN per engine
Payload	230 PAX + 10 Mg cargo	91 Mg HORUS 66-76 Mg CARGUS

As seen above the PAX version of the EHTV has far greater working hours and flight durability, this has led to the possible use of the EHTV HST version as a replacement for the Boeing 747 as a primary aircraft for transport of people or cargo at hypersonic speeds rather than subsonic. Seen below is a mass comparison of the EHTV versions and comparable aircraft.

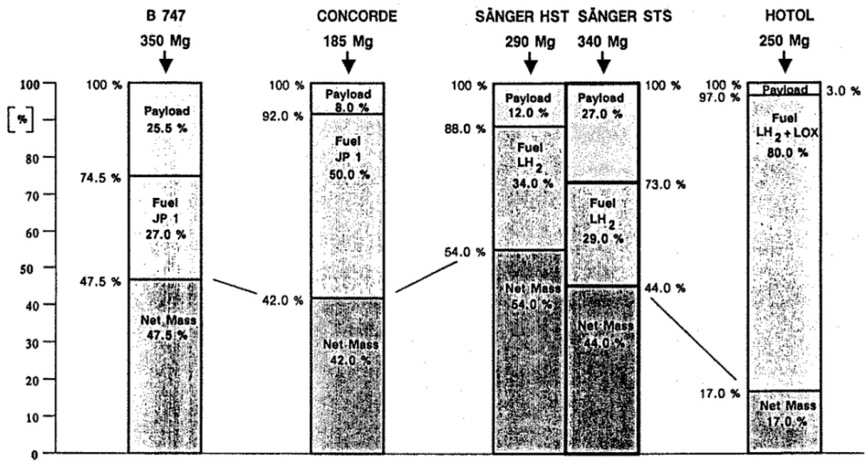


Fig. 12 Mass Comparison of Aircraft [14]

Generally speaking, the HOTOL and the X-30, ambitions projects by the UK and USA respectively are sought to function as SSTO vehicles which prove far greater complexity in terms of the development and research necessary due to requiring a net mass share of 17 % to successfully reach geosynchronous orbit not to mention the extremes at play in re-entry at Mach 25. [14] This outline how a bona fide "spaceplane" is significantly more cost intensive than a hypersonic aircraft, proving hypersonic vehicles as the more logical route to begin with.

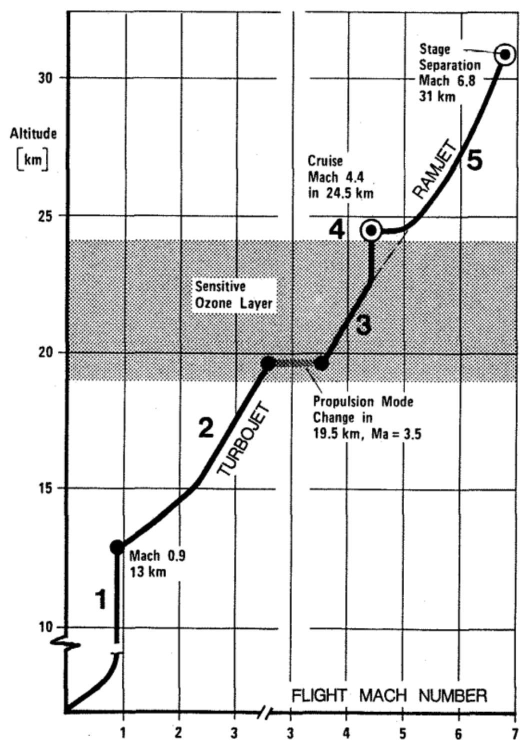


Fig. 13 Sänger Ascent Trajectory [12]

The flight profile of the Sänger craft is as follows: [14]

- Phase 1: Horizontal Take-off, ascent to 13 km via turbojet thrust to Mach 0.9
- Phase 2: Afterburner, acceleration and ascent to Mach 3.3 and 19.5 km

- Phase 3: Switch to Ramjet, acceleration and ascent to Mach 4.4 and 24.5 km
- Phase 4: Cruise
- Phase 5: Acceleration and ascent to Mach 6.8 and 31 km – stage separation
- Phase 6: Descent and horizontal landing

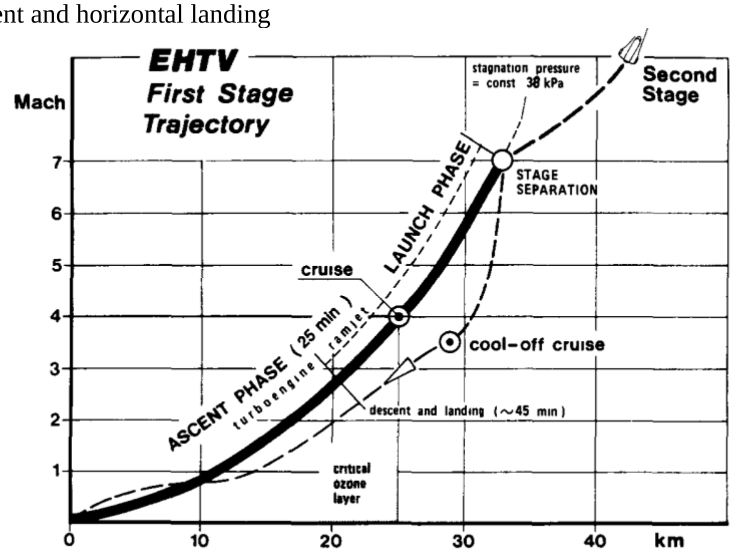


Fig. 14 Flight Profile of Sänger [13]

With the failure of the Concord in the realm of getting clearance to act as a commercial supersonic vehicle, the noise due to shocks has also been considered for the Sänger where it was found the Concord exceeded acceptable noise levels by over 50 % while the Sänger is at approximately 1/3rd the acceptable noise level limit.

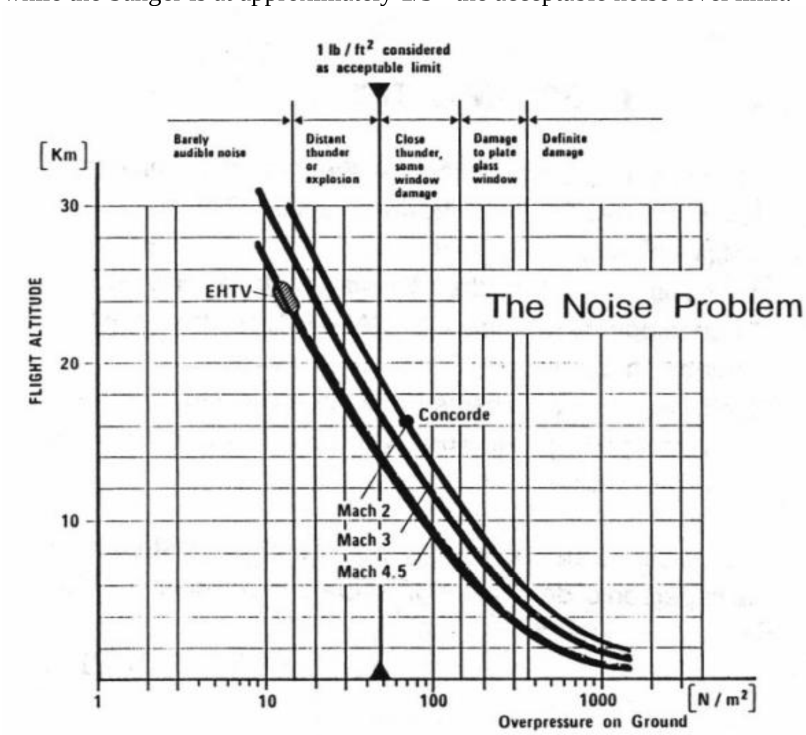


Fig. 15 Shock Noise on Ground vs Flight Speed and Altitude [14]

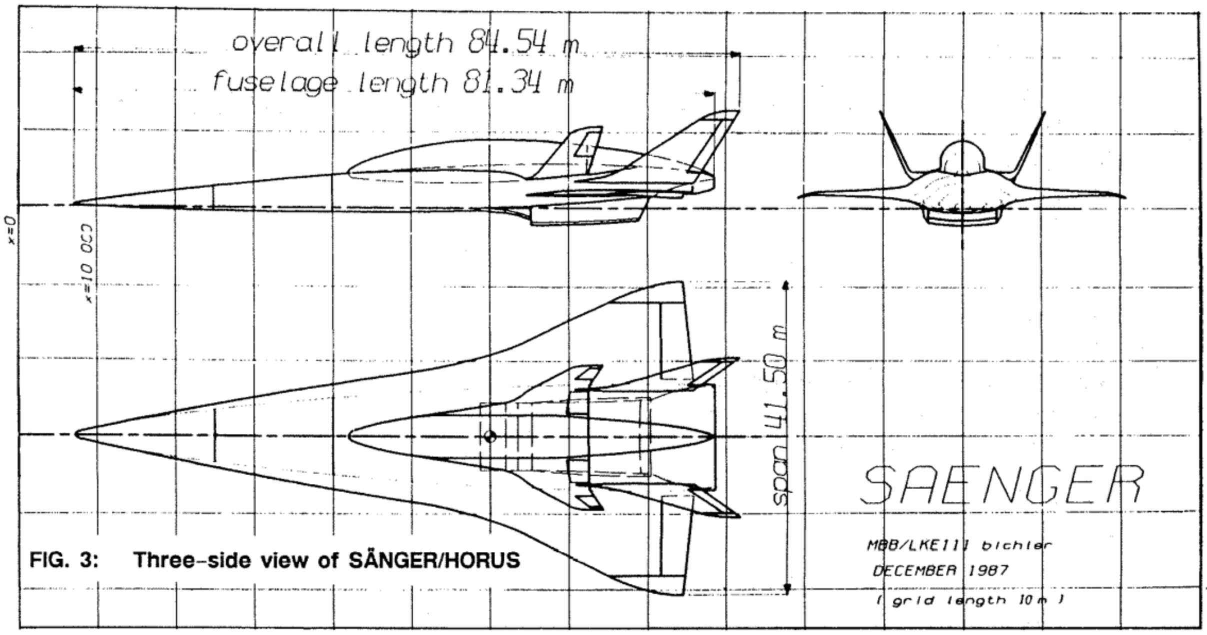


Fig. 16 Three-View of Sänger with HORUS 2nd Stage [12]

Despite the immense possibilities of the Sänger program the project was cancelled in due part to greater European cooperation in research programs as such the funding for the Sänger program dried up and was redirected to shorter term projects such as the Ariane 5 expendable rocket. [9]

D. Competition

There are various companies already working on bringing a supersonic/hypersonic vehicle to market: Boom, Jaxa, Hypermach, Gulfstream Aerospace, EADS, Aerion Corporation, Trans-Tech/UniNA, Lockheed, Northrup Gruman, Raytheon Technologies, Hermeus, GoHypersonic, UES, Spectral Engines, Ursa Major Technologies, Powdermet Inc., Goodman Technologies, and many others are involved in the research to bring such vehicles to the commercial market.

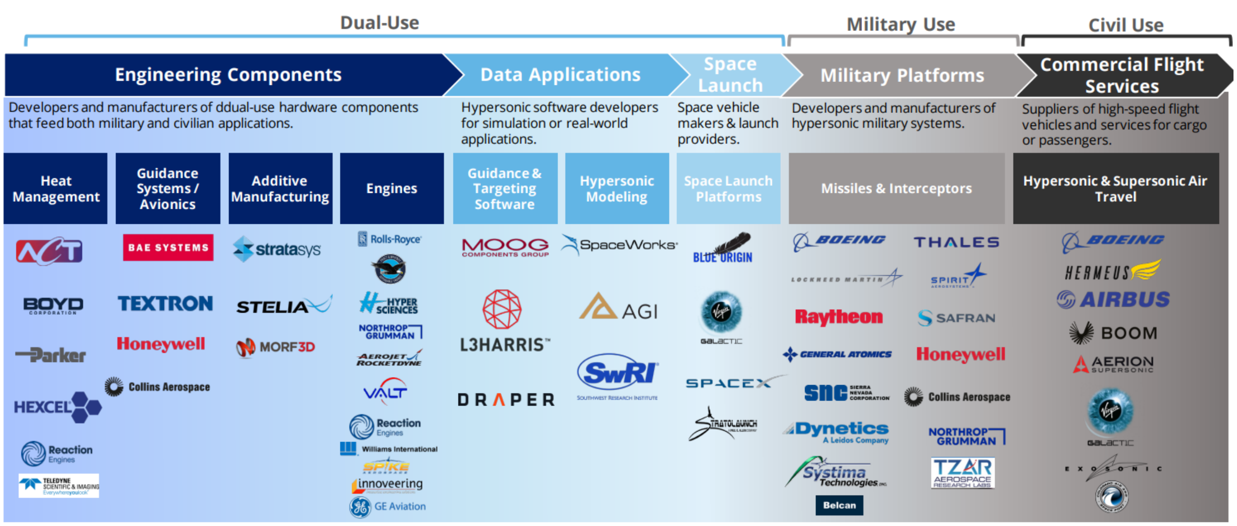


Fig. 17 Companies Working on Supersonic/Hypersonic Projects [16]

Boom

So far, the company Boom Supersonic has designed and built the XB-1 a supersonic demonstrator in order to build up the company to the first supersonic airliner. Seen below the XB-1 is a milestone for Boom in the successful completion of the Overture, the 1st supersonic airliner.

Fig. 18 XB-1 Boom Supersonic Demonstrator [17]

The XB-1 has a 71-foot fuselage, a carbon-composite airframe, a delta wing design, three J85-15 engines for 12,000 lbs. of thrust and virtual windows. [17] All in all, the design optimizes the craft for minimal weight and maximum thrust while maintaining a HOTOL capability, unsurprisingly the aircraft looks like a smaller, updated version of the Concorde. It is curious how Boom has/will deal with the immense shock noise at play in supersonic flight of which caused the Concorde to fail on an economical level.

Fig. 19 Overture by Boom [18]

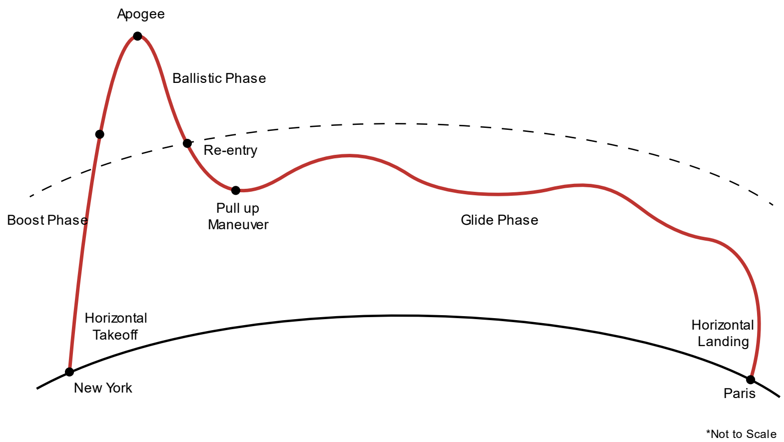
The success of the company has been on the rise with a recent partnership with the U. S. Air Force through its AFWERX and AFVentures division; the goal of this partnership is to accelerate the R&D of the Overture; the commercial supersonic airliner Boom is developing for 65 to 88 passengers. [18] The Overture is planned to be manufactured in 2023 and roll out in 2025, and flying the passengers by 2030, this program is being funded by the STRATFI Air Force funding program by $60 million. [18] Already Boom has sold 15 units of the Overture to United Airlines in a pre-purchase with another 35 in options at $200 million a pop.

E. Mission

1. *Key Mission Parameters*

The key parameters of the aircraft will define the design and design process of the aircraft.

- New York to Paris
- 10 to 50 passengers in solution space screening
- Determine and compare ROI for:
    - Commercial transport
    - Cargo transport (overnight conversion, marketability, cost, etc.)
    - Air Force One



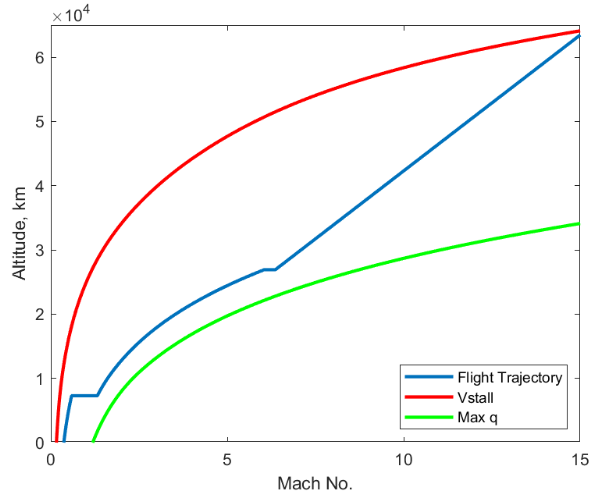


Fig. 20 Fenix Program Trajectory [19]

2. *Vehicle Design Details*

- The vehicle will initially be based on the Sänger II.
- Horizontal take-off and landing
- High altitude, supersonic flight
- TRADE STUDIES
    - PAX vs Cargo (for civil and military cases respectively) for marketing
    - Air Force One derivative
    - 10 to 50 PAX
    - RBCC vs all-rocket boost-glide design (SSTO option?)

3. *The Deliverables*

The following deliverables constitute the results of our findings after achieving the mission parameters and vehicle design details.

- Solution space generation and super positioning of finalized trade study vehicles.
- 3D print of solution spaces in good quality
- 3D print of baseline point-designs in good quality

F. Team Management

1. *Team Structure*

The team is comprised of 15 Seniors in the Aerospace Engineering degree plan.

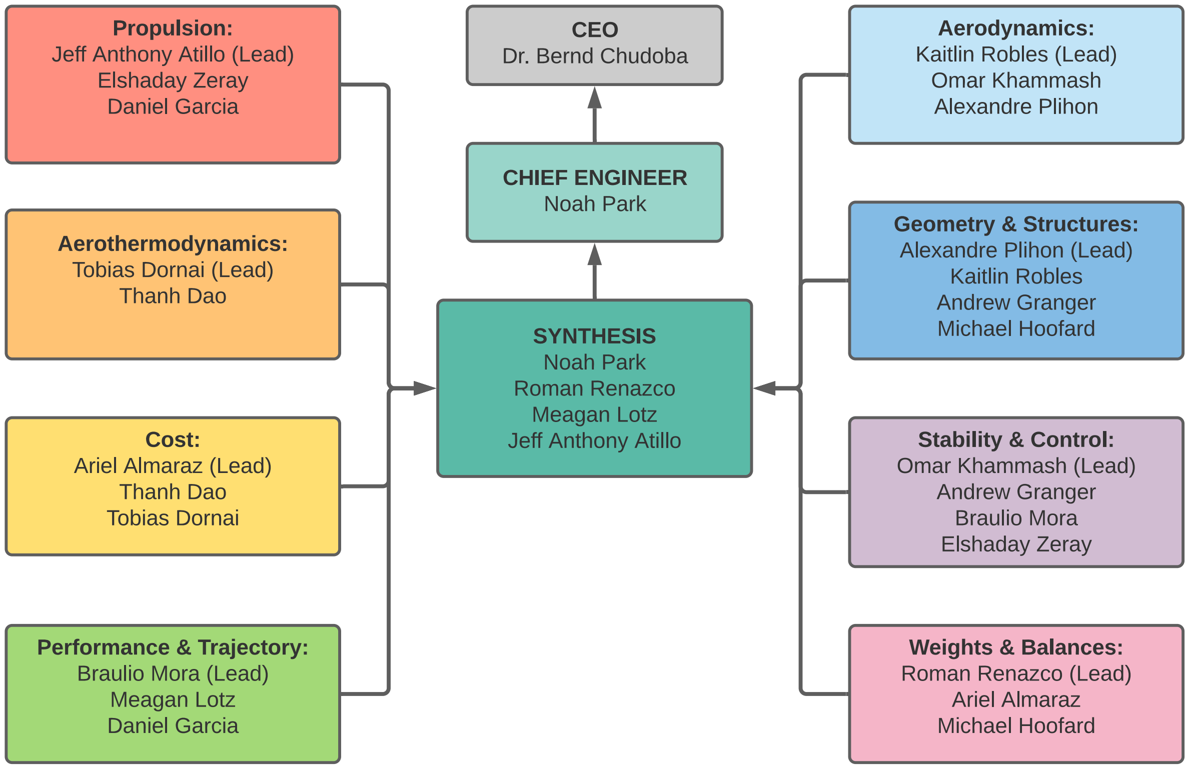


Fig. 21 Team Structure [20]

2. Semester Timeline

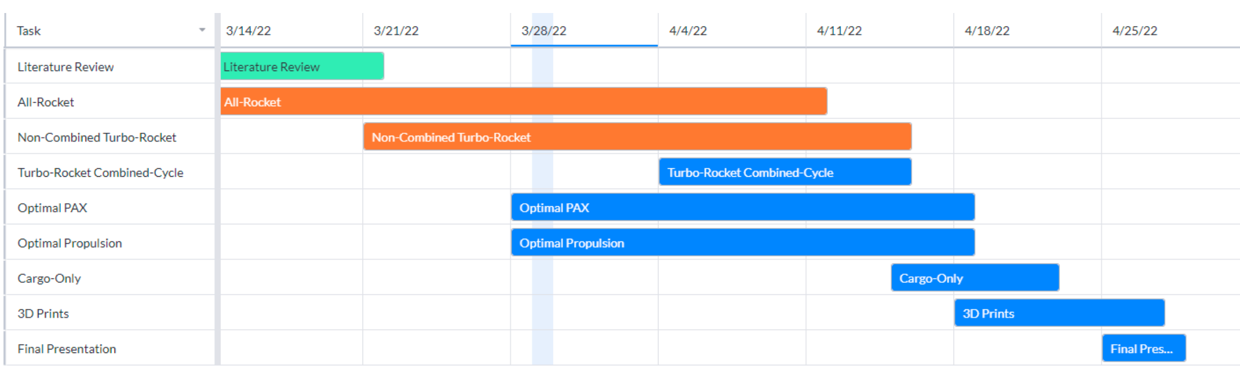


Fig. 22 Midterm to Final Timeline

II. Literature Review

The review of past research and data pertaining to the project will be split in two sections for the two disciplines the author is involved in; sub-headers delineate important overall topics that are researched upon.

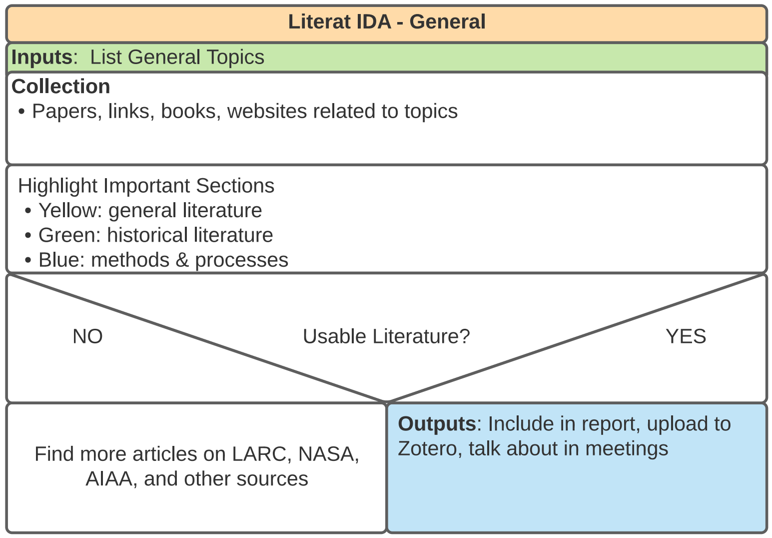


Fig. 23 General Literature IDA

A. Weights – Balances

The Weights and Balances discipline has a focus on the layout, CG determination, and component weight estimations of the vehicle. Much of the initial literature will rely on known information about Air Force One specifications, the HASA document detailing component weights for a hypersonic vehicle, information about the Sänger line of aircraft will be gleaned from textbooks on the topic and research documentation within the NASA technical reports servers. These topics will be used to build up knowledge about basing components of the Sänger II on HASA and FLOPS to compare and alter as needed for verification and plan use Air Force One documentation to provide altered and additional components to the vehicle weight to achieve the current Air Force One standards of defense for the US President.

Table 3 Weights & Balances Major Discipline Sources

#	Author(s)	Year	Work Title
1	Glatt, C. R.	1974	WAATS – A Computer Program for Weights Analysis of Advanced Transportation Systems
2	FAA	1979	SST Concorde Certification
3	Harloff, Gary J. et al.	1988	HASA-Hypersonic Aerospace Sizing Analysis for the Preliminary Design of Aerospace Vehicles
4	Gordon	2004	Concorde SST: Technical Specs
5	NASA	2006	Space Shuttle Use of Propellants and Fluids
6	Nicolai, L. M.; Carichner, G. E.	2010	Fundamentals of Aircraft and Airship Design: Volume I - Aircraft Design
7	Coleman, G. J.	2010	Aircraft Conceptual Design – An Adaptable Parametric Sizing Methodology
8	Allison, D. L. et al	2015	Development of a Multidisciplinary Design Optimization Framework for an Efficient Supersonic Air Vehicle.
9	Wells, D. P.et al.	2017	The Flight Optimization System Weights Estimation Method
10	Dababneha, Odeh	2017	A Review of Aircraft Wing Mass Estimation Methods
11	New World Encyclopedia Contributors	2019	Space Shuttle
12	Wade, M	2019	Dynasoar
13	Wade, M	2019	Saenger Antipodal Bomber

14	Wade, M	2019	Saenger I
15	Wade, M	2019	Saenger II

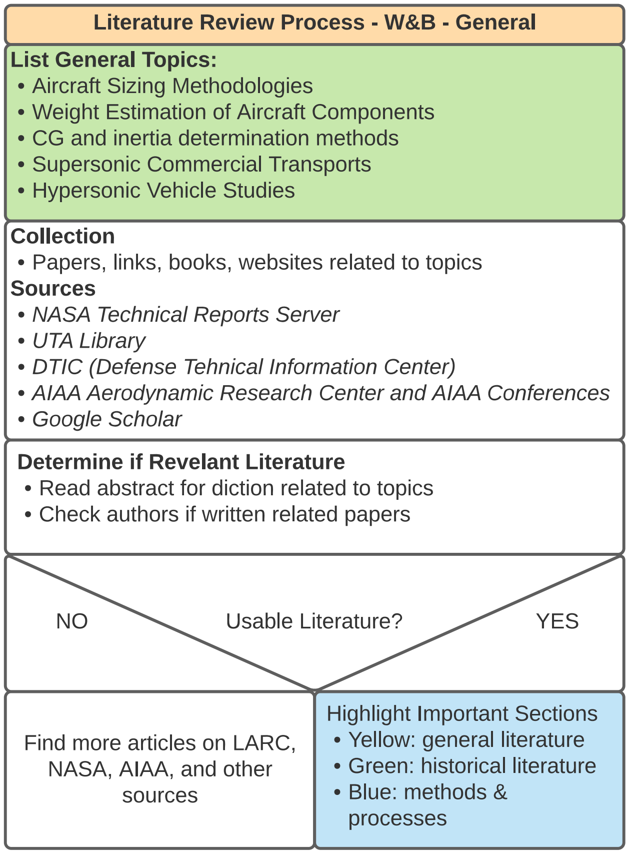


Fig. 24 W&B Literature IDA

1. Verification

Various aircraft will be used to verify the weight estimation method that has been built. The following aircraft are the surrogate aircraft that will be used with the official FLOPS software from NASA to produce detailed weight breakdowns, however it must be kept in mind the limitations of the FLOPS system.

Table 4 Verification Aircraft

Air/Spacecraft	Type	Crew	Main Payload	No. of PAX	Max Payload (kg)	Max Gross Weight/TOGW (kg)
Silverbird	Space		Ordinance	0	5000	133773
X-20 Dyna-Soar	Space	1	Ordinance	0	450	
Saenger II First Stage	Air	0	Horus	0	96000	340000
Saenger II Horus	Space	2	PAX/Cargo	36	3300	96000
Concorde	Air	11	Passengers	128	13380	185070
Tupelov Tu-144	Air	7	Passengers	120	15000	195000

Space Shuttle Orbiter	Space	8	Cargo	0	25060	110000

These aircraft have been selected for their general coverage of commercial aircraft trades and supersonic or hypersonic design. As previously mentioned only the Concorde, Tu-144 and the SSP were the only craft to have flown while the rest stayed in the conceptual phase. Seen below is a representation of each aircrafts design capabilities.

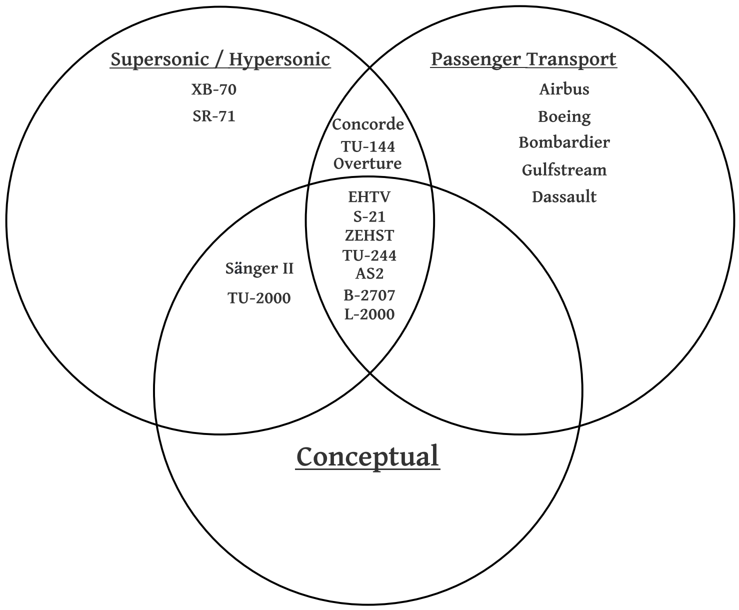


Fig. 25 Supersonic Vehicles

2. Methods

The methods used in the previous semester required intense re-evaluation due to the greater degree of complexity of designing a hypersonic TRANSPORT aircraft, rather than simply a hypersonic UAV.

FLOPS Weight and Balance Module – (Flight Optimization System) [21] [2]

- Pros:
  - New code and process, 2014
  - Extensive database of different aircraft used: fighter/transport/blended body
  - Empirical Weight Estimation (will account for the unknowables)
  - Utilizes load analysis for greater accuracy
  - Includes PAX and associated PAX systems
- Cons:
  - Only fully metallic aircraft
  - sub-sonic and supersonic aircraft, no hypersonic
  - requires significantly more inputs
  - Unusable for composite aircraft

HASA – (Hypersonic Aerospace Sizing Analysis) [22]

- Pros:
  - More general empirical weight estimation
  - Built specifically for Hypersonic vehicles
  - Include hypersonic transport conceptual designs from NASA, Hycat, and the Rockwell Space Division
  - HST, SSTO, TSTO, SST

- Able to estimate weight of engine; rocket, scramjet, turboramjet, turbojet, ramjet (except air-breathing rocket engine)
- Able to adjust material, usable for composite aircraft
- Relatively few inputs

- Cons:
  - Older method; 1988
  - Lacks detailed weight breakdown of components
  - Lacks structural analysis
  - Lacks detailed PAX adjustment values

For WAATS – (Weight Analysis of Advanced Transportation Systems) [23] [24]

- Pros:
  - Detailed PAX and associated systems in detail
  - Similar to HASA just older
  - Relies heavily on methods for the Shuttle Synthesis Program (SSSP)
  - Only minor modification necessary to work with hypersonic aircraft feasibility
  - Possibly one of the first programs for pseudo-standalone weight estimation of advanced aircraft
- Cons:
  - Older method: 1974
  - Only able to estimate weight of components not size
  - Only designed for "advanced aerospace vehicle concepts"
  - Relies heavily on methods for the Shuttle Synthesis Program (SSSP)

Assessing the above methods, the HASA methodology is unsuitable for detailed weight breakdown estimation of internal components and featured out-of-date weight estimates for electrical components due to the age of the empirical database used is from the 1980s; however, HASA was designed specifically for hypersonic vehicles leading to the external component processes being suited to this project.

To make up for the drawbacks of HASA, the weight module of FLOPS methodology will primarily be used for the internal and electrical components of the vehicle. Despite its advantages, the FLOPS weight module is only suited for fully metallic aircraft and only includes sub-sonic and supersonic aircraft, having no leeway for hypersonic aircraft, for this reason, HASA will be used for the external components. Lastly, WAATS will not be used for its similarity to HASA but is more outdated and relegated to subsonic and supersonic speed regimes.

3. Parameters

Using a synthesized flight from New York to Paris via American Airlines and the respective cargo usable from the American Airlines regulations for a Business-Class flight various weights and volumes have been calculated. In such a flight, 2 checked bags of 32 kg each are allowed with a total dimension calculation of 62 inches of which comes out to a maximum of 0.1447 cubic meters when converted per checked bag. Calculating a density of the checked bag of 221.147 kg/m3 and the allowable dimensions of a carry-on bag of 45 cm x 35 cm x 20 cm the weight and volume of a typical carry-on comes out to 7 kg and 0.0315 cubic meters respectively. [25] Similarly, using the checked bag density and the typical travel-sized backpack volume of 20 liters [26] or 0.02 cubic meters. All in all, as far as passenger cargo goes, a total volume for cargo per passenger is 0.3409 cubic meters and a total weight of cargo per passenger is 75.4 kg. Business-Class PAX seats weigh an average of 100 kg where the FAA stipulates the average man for air travel has a weight of 200 pounds or 91 kg. [27] [28]

4. HASA Equations

The equations for HASA are as follows:

$$W_b = 0.341 * mf * (\sigma)^{1.0} \quad \textbf{(1)}$$

$$\sigma = \left| \left(\frac{L_b ULF}{D_{be}} \right)^{0.15} (Q_{max})^{0.16} (S_{btot})^{1.05} \right| \quad \textbf{(2)}$$

$$W_w = 0.2958(mf) \left\{ \left| \frac{W_{emp} ULF}{1000} \right|^{0.52} \left| S_{ref} \right|^{0.7} |AR|^{0.47} \left| \frac{1+\lambda}{t/c} \right|^{0.4} \left| 0.3 + \frac{0.7}{\cos(A_{vfp})} \right| \right\}^{1.017} \quad \textbf{(3)}$$

$$W_{finh} = 0.0035(\Lambda)^{1.0} \quad (4)$$

$$\Lambda = \left| \left(\frac{W_{gtot}}{S_{ref}}\right)^{0.6} (S_{wfh})^{1.2} (Q_{max})^{0.8} \right| \quad (5)$$

$$W_{finv} = 5.0(S_{wfv})^{1.09} \quad (6)$$

$$W_{tps} = W_{ins}(S_{tb} + S_{ref} + S_{wfh}) \quad (7)$$

$$W_{thrst} = 0.00625(T_{tott}) + 69.0 \quad (8)$$

$$W_{thrurk} = 0.0025(T_{totrk}) \quad (9)$$

$$W_{str} = W_b + W_w + W_{finh} + W_{finv} + W_{tps} + W_{gear} + W_{thrst} \quad (10)$$

$$W_{gear} = 0.00916(W_{gtot})^{1.124} \quad (11)$$

$$W_{ttr} = N_{engtr} * 1782.63(e)^{0.003(W_a)} \quad (12)$$

$$W_{trj} = 0.01(T_{tott}) \quad (13)$$

$$W_{tank} = \sum \rho_{tank} V_{tank} + fuel\ tank\ insulation \quad (14)$$

$$W_{trt} = 0.00766(T_{totrk}) + 0.00033(T_{totrk})(A_{ratio})^{0.5} + 130(N_{engrt}) \quad (15)$$

$$W_{pros} = W_{tank} + W_{eng} \quad (16)$$

$$W_{hydr} = 2.64(\psi)^{1.0} \quad (17)$$

$$\psi = \left| \left(\frac{(S_{ref} + S_{wfv} + S_{wfh})Q_{max}}{1000}\right)^{0.334} (L_b + W_{span})^{0.5} \right| \quad (18)$$

$$W_{tavcs} = 66.37(W_{gtot})^{0.361} \quad (19)$$

$$W_{elect} = 1.167(\theta)^{1.0} \quad (20)$$

$$\theta = \left| (W_{gtot})^{0.5} (L_b)^{0.25} \right| \quad (21)$$

$$W_{equip} = 10000 + 0.01(W_{gtot} - 0.0000003) \quad (22)$$

$$W_{sub} = W_{hydr} + W_{tavcs} + W_{elect} + W_{equip} \quad (23)$$

$$W_{gtot} = W_{fuel} + W_{str} + W_{pay} + W_{pros} + W_{sub} \quad (24)$$

$$D_{be} = \sqrt{\frac{V_{tot}}{L * \frac{\pi}{4} * \eta_{vol}}} \quad (25)$$

$$S_{wet} = 3.309 * k_c \sqrt{L * V_{tot}} \quad (26)$$

The largest component is the support structure which is determined using the structural index seen in the following equation, of which came from the Czysz weight estimation method. [29]
.

$$\mathrm{Wstr} = \mathrm{Istr} * \mathrm{Swet} = \mathrm{Kstr} * \mathrm{Spln} * 0.138 * \mathrm{OEW} \quad (27)$$

The structural weight factor is estimated with the following relation to tau; the slenderness parameter.

$$Kstr = 0.228 * \tau^{0.206} \quad (28)$$

The tau parameter, planform area, and OEW are inputs from the Synthesis and Geometry/Structures disciplines.

5. FLOPS Weight Module Applicable Equations

$$WSC = 1.1 \times VMAX^{0.52} \times SFLAP^{0.6} \times DG^{0.32} \quad (29)$$
– Simplified form for general AC

$$\mathrm{WSC} = 2.95 \times \mathrm{SFLAP}^{0.45} \times \mathrm{DG}^{0.36} \quad (30)$$
- Fighter/Attack AC

$$WSC = 0.404 \times SW^{0.317} \times \left(\frac{DG}{1000}\right)^{0.602} \times ULF^{0.525} \times QDIVE^{0.345} \quad (31)$$
– General AC

$$QDIVE = 1481.35 \times DELTA \times VMAX^2 \quad (32)$$

$$WAPU = 54 \times FPAREA^{0.3} + 5.4 \times NPASS^{0.9} \quad (33)$$

$$WIN = 0.48 \times FPAREA^{0.57} \times VMAX^{0.5} \times (10 + 2.5 \times NFLCR + FNEW + 1.5 \times FNEF) \quad \textbf{(34)}$$

$$WHYD = 0.57 \times (FPAREA + 0.27 \times SW) \times (1 + 0.03 \times FNEW + 0.05 \times FNEF) \times \left(\frac{3000}{HYDPR}\right)^{0.35} \times (1 + 0.04 \times VARSWP) \times VMAX^{0.33} \quad \textbf{(35)}$$

$$WELEC = 92 \times XL^{0.4} \times WF^{0.14} \times NFUSE^{0.27} \times FNENG^{0.69} \times (1 + 0.044 \times NFLCR + 0.0015 \times NPASS) \quad \textbf{(36)}$$

$$WAVONC = 15.8 \times DESRNG^{0.1} \times NFLCR^{0.7} \times FPAREA^{0.43} \quad \textbf{(37)}$$

$$WFURN = 127 \times NFLCR + 112 \times NPF + 78 \times NPB + 44 \times NPT + 2.6 \times XLP \times (WF + DF) \times NFUSE \quad \textbf{(38)}$$

$$WAC = (3.2 \times (FPAREA \times DF)^{0.6} + 9 \times NPASS^{0.83}) \times VMAX + 0.075 \times WAVONC \quad \textbf{(39)}$$

$$WAI = \frac{B}{\cos(SWEEP)} + 3.8 \times FNAC \times FNENG + 1.5 \times WF \quad \textbf{(40)}$$

$$WFLCRB = \begin{Bmatrix} NFLCR \times (215 - 35 \times CARBAS), & \text{for fighter/attack aircraft} \\ NFLCR \times (225 - 35 \times CARBAS), & \text{otherwise} \end{Bmatrix} \quad \textbf{(41)}$$

$$NSTU = \begin{Bmatrix} 0, & \text{for } NPASS \le 0 \\ 1, & \text{for } 0 < NPASS < 51 \\ 1 + \left\lceil \frac{NPASS}{40} \right\rceil, & \text{for } NPASS \ge 51 \end{Bmatrix} \quad \textbf{(42)}$$

$$NGALC = \begin{Bmatrix} 0, & \text{for } NPASS < 151 \\ 1 + \left\lceil \frac{NPASS}{250} \right\rceil, & \text{for } NPASS \ge 151 \end{Bmatrix} \quad \textbf{(43)}$$

$$NFLCR = \begin{Bmatrix} 2, & \text{for transport and HWB aircraft with } NPASS < 151 \\ 3, & \text{for transport and HWB aircraft with } NPASS \ge 150 \\ 1, & \text{for fighter/attack and general aviation aircraft} \end{Bmatrix} \quad \textbf{(44)}$$

$$WUF = 11.5 \times FNENG \times FTHRST^{0.2} + 0.07 \times SW + 1.6 \times NTANK \times FMXTOT^{0.28} \quad \textbf{(45)}$$

$$WOIL = 0.082 \times FNENG \times FTHRST^{0.65} \quad \textbf{(46)}$$

$$WCON = 175 \times NCON \quad \textbf{(47)}$$

$$WSTUAB = NSTU \times 155 + NGALC \times 200 \quad \textbf{(48)}$$

$$NCON = \left\lceil \frac{WCARGO}{950} \right\rceil \quad \textbf{(49)}$$

$$WSRV = (5.164 \times NPF + 3.846 \times NPB + 2.529 \times NPT) \times \left(\frac{DESRNG}{VMAX}\right)^{0.225} \quad \textbf{(50)}$$

$$NPASS = NPF + NPB + NPT \quad \textbf{(51)}$$

$$WPASS = NPASS \times WPPASS \quad \textbf{(52)}$$

$$WPBAG = BPP \times NPASS \quad \textbf{(53)}$$

$$WCARGO = CARGOW + CARGOF \quad \textbf{(54)}$$

$$BPP = \begin{Bmatrix} 35, & \text{for } 1 \leq DESRNG \leq 900 \\ 40, & \text{for } 900 < DESRNG \leq 2900 \\ 44, & \text{for } 2900 < DESRNG \end{Bmatrix} \quad (55)$$

$$FUFU = FUELM - FULWMX - FULAUX \quad (56)$$

$$FMXTOT = FULWMX + FULFMX + FULAUX \quad (57)$$

$$FULWMX = FULDEN \times FWMAX \times SW^2 \times TCA \times \left(1.0 - \frac{TR}{(1.0+TR)^2}\right) / SPAN \quad (58)$$

B. Synthesis

The Synthesis discipline will be focusing on the Parametric Sizing phase of Conceptual Design, in this case there are two main sources of information utilizing Hypersonic Convergence; the "Future Spacecraft Propulsion Systems and Integration" textbook by Czysz and a thesis on the topic of Conceptual Design by Coleman, these will be used to further refine and improve Hypersonic Convergence programming created previously. In the authors case there will be a focus on delivering crew and systems sizing using preliminary weight and volume estimation as gleaned from literature

Table 5: Discipline Research - Synthesis General

ID	Author	Year	Title
1	Czysz	1995	Definition of the design space in which convergence can occur with a combined cycle propulsion system [30]
2	Ingenito, Gulli, Bruno	2010	Preliminary Sizing of an Hypersonic Airbreathing Airliner [31]
3	Chudoba, Coleman, Oza, Gonzalez, Czysz	2012	Solution-Space Screening of a Hypersonic Endurance Demonstrator [1]
4	Omoragbon	2016	Complex Multidisciplinary Systems Decomposition for Aerospace Vehicle Conceptual Design and Technology Acquisition [32]
5	Rana	2017	Space Access Systems Design: Synthesis Methodology Development for Conceptual Design of Future Space Access Systems [33]
6	Rana, McCall, Haley, Chudoba	2017	Conceptual Design Solution Space Identification and Evaluation of Orbital Lifting Reentry Vehicles based on Generic Wing-Body Configuration [34]
7	Czysz, Bruno, Chudoba	2018	Future Spacecraft Propulsion Systems and Integration [35]
8	Chudoba	2018	Generic Hypersonic Vehicle Design Configuration Verification [36]
9	Rana, McCall, Haley	2018	A Paradigm-Shift in Aerospace Vehicle Design Synthesis and Technology Forecasting [37]
10	Raymer	2018	Aircraft design: a conceptual approach [38]

***1. Conceptual Design** [39]*

Conceptual Design is the initial step to designing an aircraft to specification, with the result of presenting a feasible aircraft. However, this design lacks the refinement of a mature design which is addressed in the next step known as Preliminary Design, and most assuredly lacks the development of a shop design which is addressed in the Detailed Design step. The Conceptual Design process consists of 3 parts. [40]

- Parametric Sizing
- Configuration Layout
- Configuration Evaluation

The first of these, Parametric Sizing, creates the 1st order solution space based on past designs and iterated variables creating a large database of designs. This phase of the conceptual design process answers the question of whether the mission is feasible and if further technology is required for meeting said mission's requirements. [41] In doing so, preliminary sizing determines the risk and cost involved with a project by rapidly screening configurations and applicable technology. The process requires 3 inputs to begin. [41]

- Fixed mission requirements
- Gross aircraft configuration concepts
- Disciplinary technology assumptions

The following are elements of the parametric sizing process: [41]

- OEW estimation
- Trajectory Analysis
- Convergence Logic
- Constraint Analysis
- Sizing Logic
- Trade Studies

Parametric sizing uses these inputs and these elements to produce the following deliverables: [41]

- Gross geometry database of aircraft
- Weight estimates of multiple aircraft configurations
- Operating/Maintenance cost of aircraft

The 2nd step is the Configuration Layout phase of the conceptual design process. This phase is the creative portion of the design process, relying heavily on the prior experience and intuition of those involved. The focus of this phase lies in the refinement of the solution space created by the parametric sizing phase of conceptual design. The following constitute the deliverables of configuration layout:

- Integration and layout of major aircraft components such as the vertical tail and control surfaces.
- Fill in design details of solution space designs required for Configuration Evaluation.
- Find and prove/disprove certain assumptions in parametric sizing are valid.

The configuration layout phase requires the solution space derived from configurations and technologies identified during the parametric sizing phase. If invalid assumptions are found, reiteration back to parametric sizing would be required to correct the solution space.

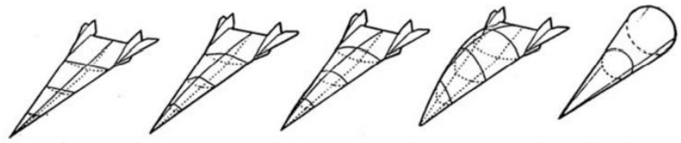
The final phase of the conceptual design process, Configuration Evaluation, serves to determine what conceptual design *"…best meets the mission requirements…"* [41] This is a highly multi-disciplinary process integrating multiple disciplines to evaluate aircraft configurations. This process requires sized and laid out configurations, of which are provided by the configuration layout phase of conceptual design. This phase serves the following purposes:

- Check critical design assumptions used in the parametric sizing phase.
- Refine design decisions made in the configuration layout phase.
  Select a design point for the final design by comparing performance metrics to the mission specifications.

2. Hypersonic Convergence *[39]*

Hypersonic Convergence is a revolutionary way for aircraft synthesis in how the process solves for the weight and volume of an aircraft simultaneously for a perfected design. A Preliminary Sizing method, this aircraft sizing methodology hinges on a non-dimensional volume index, τ which establishes the volume to planform area ratio also called slenderness, this is also known as the Küchemann slenderness. Rather than an initial assumption as the parametric sizing in Loftin resembles, Hypersonic Convergence has a different approach yielding combinations of geometries rather than individual point designs. "*Given propulsion system characteristics and industrial capability, the result is a continuum of configuration concepts (solution topography) derived from the values of these geometric parameters that permit convergence within the technology limits set by the structural and propulsion indices. Thus, the converged configuration is a result of a multi-disciplinary parametric analysis and not an initial assumption*." [35] In doing so, a better design is achieved when the convergence of constraints and mission requirements is finally reached; the more iterations the closer to the ideal aircraft for a specific mission is found.

This variation of the volume index τ and other variables, yield drastically different designs that can define an aircraft to fit mission specifications; these difference in design for hypersonic aircraft are seen in Fig. 26.



	Minimum	Slender	Nominal	Stout	Circular Cone
tau	0.032	0.063	0.104	0.229	0.393
K_W	2.44	2.51	2.64	3.39	3.61
$\beta \cdot C_{D0}$	0.0613	0.0639	0.0574	0.0809	0.0980
L/D M = 12	4.82	4.71	4.57	4.13	3.70

Fig. 26: Küchemann slenderness, τ, and other parameter effects on geometry [1]

Besides blended-body designs, this Küchemann slenderness parameter may be applied to various other aircraft configurations. In Fig. 27 the wetted area over the planform area ratio resulting from Küchemann's tau parameter is seen. A variety of aircraft are seen in resulting from this parameter, wave riders, blended-bodies and lifting-bodies.

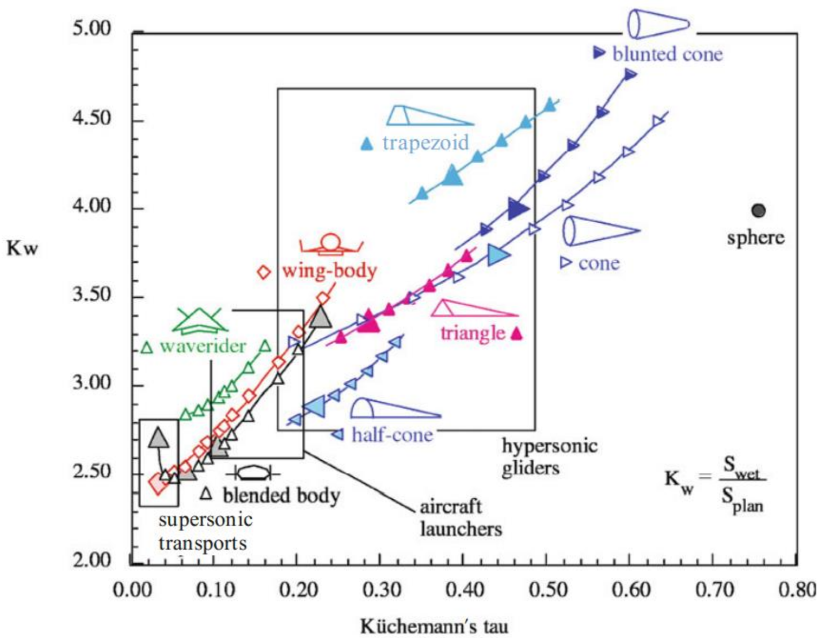


Fig. 27: Kw vs τ [35]

The second objective of Hypersonic Convergence is to compare the initial guess of wing loading on the geometry matches the wing loading output of the system, in a feedback loop of sorts. [42] This has been used previously in Generic Hypersonic Vehicle (GHV) sizing and verification using the Database Management System (DBMS). GHV development using Hypersonic Convergence lie in the iteration of slenderness and planform area until a weight and a volume budget converge. These converged designs are stored and plotted along lines of cruise endurance and volumetric efficiency and take-off-gross-weight and planform area to determine the best designs . [36] This comparison of designs and selection of a design point is seen in Fig. 28.

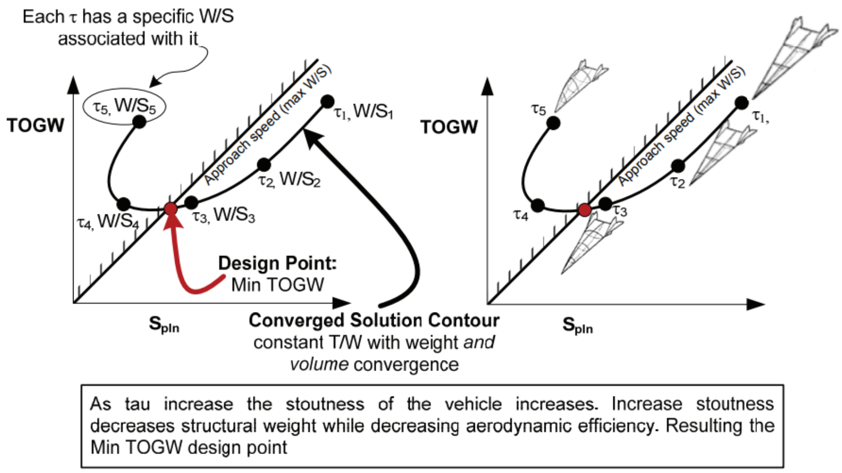


Fig. 28: Hypersonic Convergence Sizing Model [41]

Hypersonic Convergence relies on the convergence of a weight budget and volume budget which are calculated with the following equations.

$$OEW_w = \frac{W_{str}+C_{sys}+W_{oper}+(T/W)_{max}WR/E_{TW}(W_{pay}+W_{crw})}{\frac{1}{1+\mu_a}-f_{sys}-(T/W)_{max}WE/E_{TW}} \tag{1}$$

$$OEW_v = \frac{\tau \cdot S_{pln}^{1.5}(1-k_{vv}-k_{vs})-V_{fix}-V_{pay}-V_{crew}}{\frac{WR-1}{\rho_{fuel}}+k_{ve}(T/W)_{max}WR} \tag{2}$$

These parameters will have the involved parameters initially iterated then refined in the Configuration Layout and Configuration Evaluation phases of the design process. Seen in Fig. 29 there are 5 main components to the Hypersonic Convergence: Operating Empty Weight Estimation, Trajectory Analysis, Constraint Analysis, and Convergence Logic, the last one being Eq. (2) and Eq. (3) seen above.

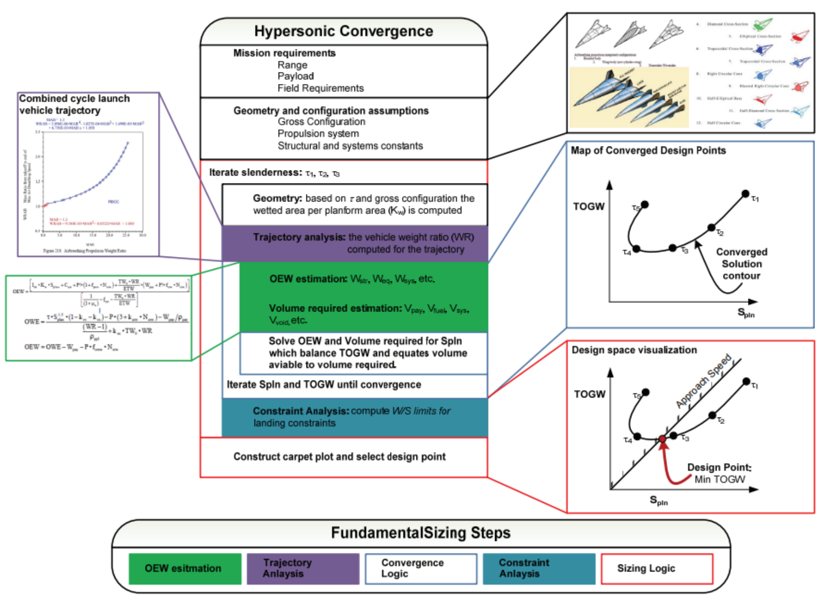


Fig. 29: Hypersonic Convergence Method [41]

The Hypersonic Convergence logic holds great value in hypersonic aircraft due to the increased connectedness of the parts of a vehicle and how they affect each other while at high speeds. Take wave-riders for instance, they lack the traditional clear cut components of a fuselage, wings, and tail parts as in typical trans-sonic aircraft such as the Boeing 747; these wave-riders are often blended bodies featuring the integration of many parts of the aircraft. [43] This is done due to the intricate relationships between each of these parts holding far greater importance and effect on the performance of an aircraft while at higher speeds just like a smooth road is needed for a racetrack as opposed to a dirt one for a farm truck, Hypersonic Convergence achieves these ends. The difference between typical aircraft and hypersonic aircraft is seen in Fig. 30.

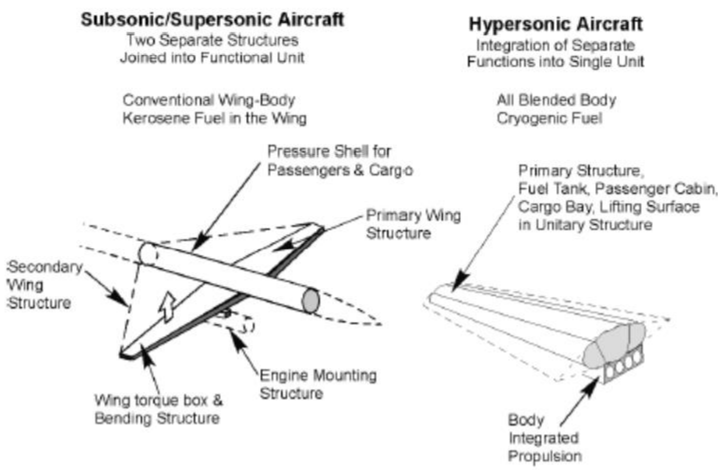


Fig. 30: Subsonic/Supersonic vs Hypersonic Aircraft [41]

However, there are numerous methods and systems for Synthesis, these are tabulated in Appendix B: Aircraft Synthesis Methods as complied by the AVD Laboratory. [32] While various synthesis methodologies exist each are evaluated on a few common factors; ability of the system to model vehicles involving multiple disciplines, to combine hardware and assess multidisciplinary effects on said hardware, how applicable the system is to products, the adaptability of the system to new technologies, the flexibility of the system to match changing parameters during a products lifetime, and lastly if the system provides a methodology for varying mission requirements and requirement analysis. [32] These are noted in Table 6 as system capability.

The currently most used method for aircraft design is the Loftin sizing method which is similar to the Hypersonic Convergence method but only relies on a weight budget, this is based on a *"...constant gross weight analyses and photographic scaling as the primary approach for conducting design trades*." [35] The Loftin and related methods mainly used in today's aircraft join separate structures into a functional unit, where each structure is "optimized" somewhat independently. This is seen in the common "stick with wings" aircraft that fill the skies today all of which lack each *part* being designed to work effectively and in conjunction with one another. In the conventional sense, this is economical and acceptable for sub-sonic aircraft designs, as aircraft designed with this method are far simpler geometrically, thus significantly cheaper to produce as compared to integrated designs which increase complexity.

However, for highspeed designs in the supersonic and hypersonic regimes this is not viable. At these speeds 3 main challenges lay as impediments to the journey into these speed regimes. [44]

- Heat
- Advanced Materials
- Maneuverability

At such extreme speeds friction due to air resistance generate heat extremes. To combat this heat air resistance and the aerodynamic qualities of a design must be optimized to the best ability, this is where Hypersonic Convergence enables the design of hypersonic vehicles, by optimizing every part of a vehicle with each other. Rather than considering a design as separate parts the Hypersonic Convergence method considers an aircraft as a single entity. Similarly, new advanced composite materials are another avenue to mitigate the negative effects of the extreme conditions.

Thirdly, due to the boundary layer effects at hypersonic speeds, changes in the pressure distribution on an aircraft and due to the high speeds in general the maneuverability of aircraft becomes difficult, where conventional control surfaces become inoperable. This was seen during WWII where pilots dog fighting would reach supersonic speeds by nose diving, however, due to the changes of the boundary layer interactions with the control surfaces pilots had no control of their aircraft to pull up in a nosedive. The first aircraft to successful reach supersonic speeds and land safely was the Bell X-1, of which had innovative control surfaces able to provide some control in the supersonic regime but still featured "… (would reach) *extremely high angles of attack, between 45 and 60 degrees, and then it would start to roll violently, so the aircraft became completely and totally out of control - just spinning around in the sky*." [45] With even greater speeds the effectiveness of control surfaces evolves where a balance is required for a single stage to orbit aircraft to have usable control surfaces in the trans-sonic, supersonic, and hypersonic speed regimes.

With these challenges in mind, Hypersonic Convergence provides an avenue to solve the heat problem with improved aerodynamics. By featuring a better method for designing an aircraft for higher speed regimes features an improved system capability by proving more 'design phase applicability', the 3rd step in the System Capability assessment seen in Table 6.

Table 6: System Capability [32]

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

Hypersonic Convergence fits the system capability criteria for supersonic and hypersonic aircraft, while showing minor improvements in trans-sonic aircraft. The iterative nature and integration of each 'section' of an aircraft into a single solution space causes Hypersonic Convergence to be an excellent method for this project focusing on the development of a hypersonic aircraft. For these reasons Hypersonic Convergence is the best methodology for producing the hypersonic aircraft for this project.

3. Roskam Preliminary Design I

A Configuration Layout method known as the Roskam Preliminary Design I and a similar method known as Raymer's method are popular choices for aircraft design, and both are applicable to hypersonic aircraft. An overview for the Roskam and Raymer's methodologies are found in **Error! Reference source not found.** and **Error! Reference so urce not found.** respectively. The Configuration Layout section of the Roskam Preliminary Design I process is outlined in Fig. 31. Overall, this process relies on empirical data from an extensive database of aircraft and iteration of parameters until the weight converges with the design. [41]

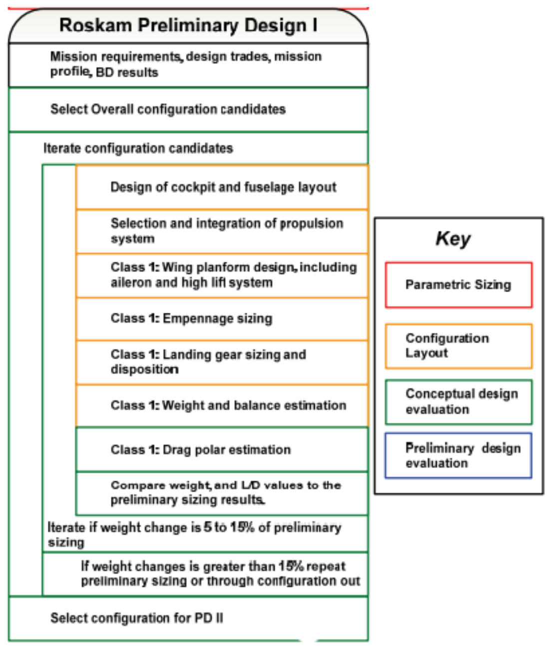


Fig. 31: Roskam Preliminary Design I - CL Process [41]

4. PrADO Methodology

A Configuration Evaluation method, PrADO is considered one of the most capable methods to date for this phase of the Conceptual Design process. [41] An overview of the method is seen in **Error! Reference source not found.** in REF _Ref85489001 \h **Error! Reference source not found.**. Also known as Preliminary Aircraft Design and Optimization, this method is unique from other Configuration Evaluation methods in its degree of integration of disciplinary modules into an effective database allowing for rapid changes of parameters, disciplines, or geometries, as such, provides a route to incorporate optimization processes to further refine the design.[41]

The PrADO process is seen in Fig. 32 where the convergence logic is incredibly versatile, able to include analytical, numerical, or empirical methods, this includes Hypersonic Convergence.

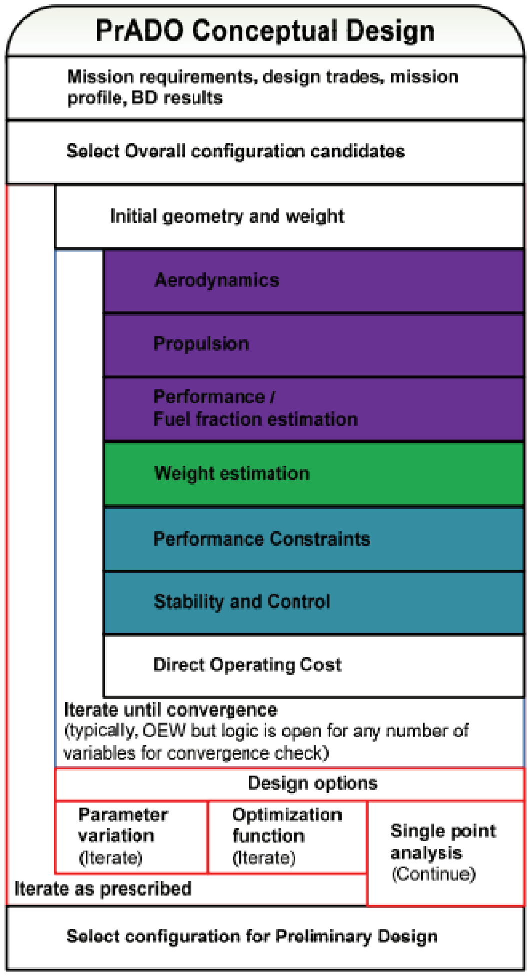


Fig. 32: PrADO Conceptual Design Process [41]

The PrADO conceptual design process has 4 main attributes that develop this method into being one of the best and most robust Configuration Evaluation methods out there. [41]

- Modular Design: a custom database system of text files enabling *"…modules to access the latest model data*." [41] This structuring opens the code for additional methods and functions to be incorporated.
- Disciplinary Method Robustness: effectively a library of disciplinary methods for modules to call from directly; this would include methods of analytical, empirical, and numerical properties.
- Data Visualization: Capable of being linked to a CAD Kernal visualizing the geometry of designs.

Configuration Robustness: Wide aircraft type application

C. Marketability

The market viability of this project is crucial as any product created that doesn't cater to a need or want properly will never turn a profit as was the case with the supersonic transport the Concorde. The programs main benefit lay with the time savings possible with supersonic and hypersonic aircraft, the publics willingness to pay premiums for this saved time is used as a metric to determine the marketability of such aircraft.

1. The Basics

Historically speaking, supersonic and hypersonics have been reserved for the military however today that is changing with a renewed focus by the government to cut-down the red tape and R&D barriers to the civil market such as NASA's QueSST program and high-dollar funding of other projects through the Advanced Air Vehicle Program (AAVP). Even with government support high-speed air travel will fall under premium air travel due to high fees relative to the existing air-transportation however there are the benefits of efficiency over long distance, time saved, and experimental value each adding to the perceived value of high-speed air travel.

There are three main customer bases:

- Commercial Passenger Service – supersonic/hypersonic transport akin to Concorde
- Cargo Service – expedited shipping for luxury/exotic goods
- Private Jet – faster aircraft for private owners and jet-sharing entities

Each market requires a differently equipped vehicle, however aircraft in general are flexible in nature often having modular designs leading to low manufacturing cost differences between each market. An example of this is in how large airliners often carry passengers during the day and are converted at night to ferry cargo around the world.

2. Route Selection

There are critical locations where high-speed air-travel would be economically viable primarily depending on the following critical location factors: [16]

- Crown Jewel Competitiveness – outsized revenue performance routes → favorable economics
- Route Toughness – multiple non-dominant provider routes → location barrier
- Demand Drivers – routes with large passenger/cargo volumes → favorable conditions
- Customer Socioeconomics – concentrations of wealthy individuals → enough clients/customers
- Technical Factors – technical viability in terms of the physical and regulatory

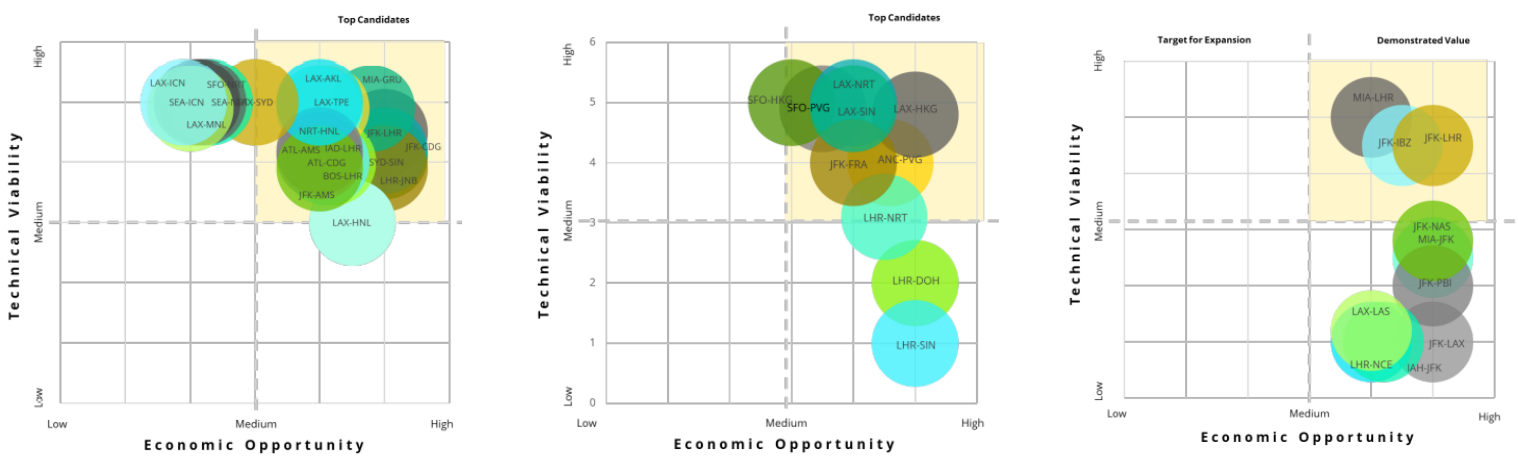


Fig. 33 City-Pairing Results for Passenger (left), Cargo (Center), and Private Jet (Right) [16]

These factors have resulted in the most feasible city-pairings being in coastal regions, with large metropolitan development, destination popularity, wealthy population connected to tech and/or industrial base, and trans-oceanic routes. Most of the best routes centered around the JFK airport to cities around the globe.

3. Demand & Pricing

The demand for each market, passenger, cargo, and private jet depends heavily on how much time is saved and at what cost however the price elasticity and demand varies across each market-base.

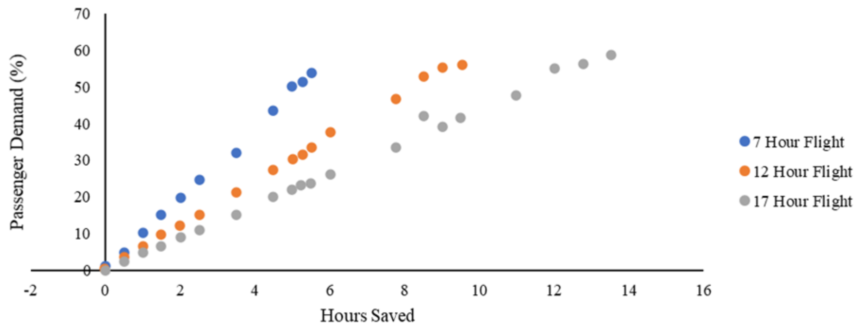


Fig. 34 Hours Saved vs Passenger Demand

The commercial passenger market will pay higher premiums to save time with the highest demand at 2x to 6x the original economy price. Coming out to a whopping $2B revenue for a Mach 2 passenger route for JFK-LHR in only the 1st year of service. This comes out to $17B in annual revenue on the most viable routes. [16] However, the demand elasticity and willingness to pay a premium varies across mid-haul, long-haul, and ultra-long-haul routes; with greater demand for mid-haul flights but greater premiums on ultra-long-haul flights.

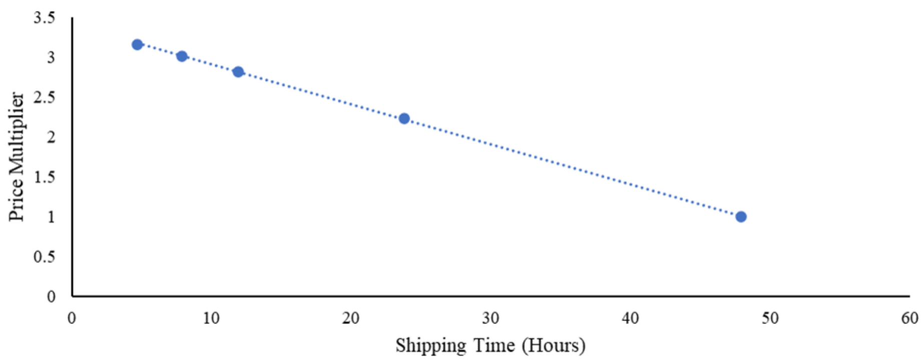


Fig. 35 Shipping Time vs Shipping Price Premium

The cargo transport market has various applications from organ transport to military hardware having time-sensitive demand in both the private and government sectors supersonic shipping creates a market unto itself with the highest demand at 5x the current shipping prices representing a $21B market for 12-hour and 5-hour shipping in the first year of service.

Lastly, the private jet market differs from the other two in having different models for aircraft use focusing on an aircraft's range, economical operations, cabin luxuries, manufacturer, cabin size, aircraft age prior considering cost.

- Ownership – sole or fractional ownership
- Jet Card/Membership – pre-paid program for hours of flight or dollars to a specific hourly rate
- Charter Service – on-demand aircraft to meet clients' needs

As such, for means of private jet transport the focus would consider the aircraft as a luxury good, where most wealthy individuals have 14.6% of their wealth in high-value assets which is used to represent an affordability celling. [16] A full 30% of private jet owners are interested in supersonic airframes pointing to a market of $2 to $12B in the first year. [16]

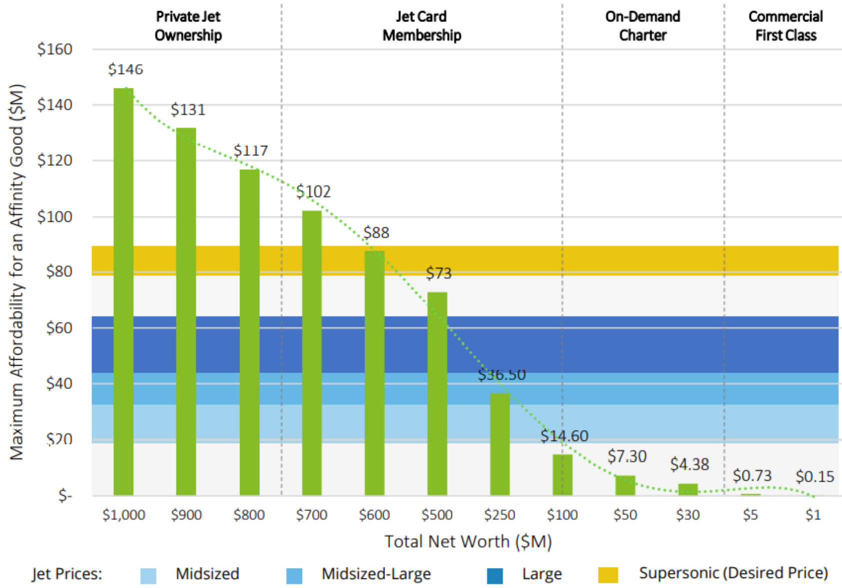


Fig. 36 Private Ownership Affordability [16]

4. Supersonic Historical Market

With all these massive profits why haven't we been able to fly to Paris in a couple hours? In the past, various projects have taken place to conquer this speed regime.

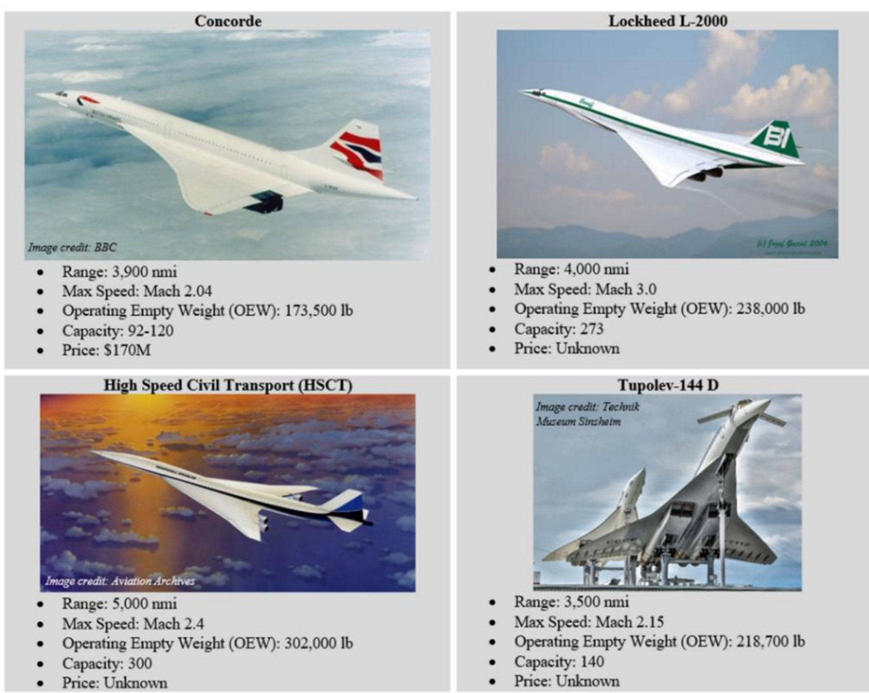


Fig. 37 Legacy Supersonic Transport Aircraft

Unfortunately, many of these vehicles either couldn't turn a profit or were canceled, all being ahead of their time technologically speaking and marred with regulatory tape. However, that changes today, already many startups and companies are developing their own vehicles.

Fig. 38 Modern Supersonic Projects/Programs

5. Optimal Design for Market

There are viable business cases for high-speed civil transport supersonic and hypersonic aircraft depending on a variety of factors such as passenger volume, speed, range, pricing, and consumer demand in this nascent industry. The results of a comprehensive market study showed the most optimized business models preferred smaller jets to serve both commercial airline and private jet markets as seen below.

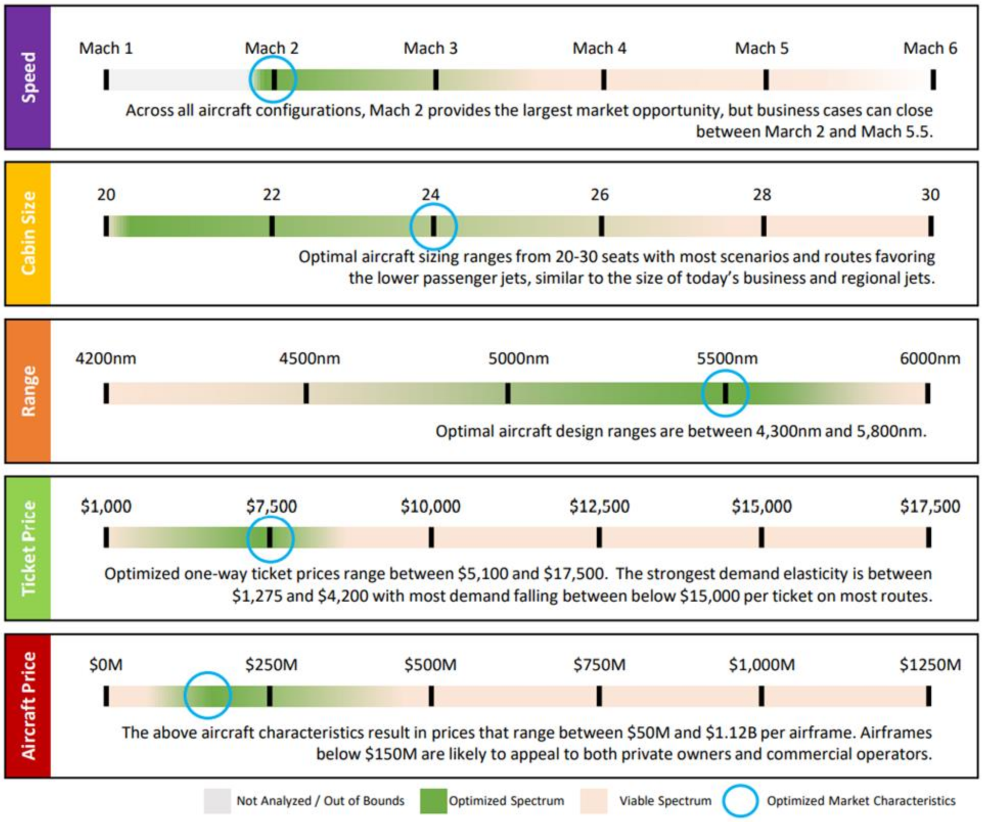


Fig. 39 Optimized Design Characteristics for Viable Business Case [16]

These designs have been optimized based on the estimated IRR (Internal Rate of Return) a metric on how profitable a venture is considering the accrued fuel costs, manufacturing costs, demand available, technical feasibility/complexity among other factors. The following table outlines the most market-worthy vehicle design specifications leaning toward a Mach 2 low-boom aircraft.

Table 7 Market Optimal Design Qualities

Aircraft/Market Characteristics	Optimized Market
Aircraft Speed	Mach 2 – Mach 4
Passenger Capacity	20 – 30
Range	4300nm – 5800nm
Approximate Ticket Cost	$5,100 - $17,500
Approximate Aircraft Cost	$50M - $400M
Annual Passenger Demand	2.2 M – 3.45 M
Aircraft Sold	242 - 548

However, the optimal designs vary drastically by Mach number, adjusting the business-case each time as seen below.

Fig. 40 Range vs Average IRR for each Mach [16]

6. Barriers to Market

Despite these optimistic outlooks there are various barriers-to-market posing risks to a venture the most prominent being routed in regulatory compliance lacking clarification preventing high-speed aircraft from entering service.

Table 8 Barrier Heat Map [16]

Challenge	Compliance	Solution	Investment	Ease of Use	Community	Total	Rank Categorization[1]
1. Sonic Boom Restrictions	3	2	3	2	3	13	**Barrier**
2. Aircraft Certification	3	3	3	1	2	12	**Barrier**
3. Landing & Takeoff Noise	2	2	2	1	3	10	**Barrier**
4. Emissions Standards	2	2	2	1	2	9	**Significant Challenge**
5. Export Controls	3	1	2	2	1	9	**Significant Challenge**
6. Depressurization Event	1	1	2	2	2	8	**Minor Challenge**
7. Alternative Fuels	2	2	2	1	1	8	**Minor Challenge**
8. International Laws	2	2	2	1	1	8	**Minor Challenge**
9. Heat Sensitivity	1	2	2	2	1	8	**Minor Challenge**
10. NAS Integration	2	1	1	2	1	7	**Minor Challenge**
11. Anomalous Radiation Events	2	1	1	1	2	7	**Minor Challenge**
12. Flight Shaming	1	1	2	1	2	7	**Minor Challenge**
13. Runway Length	1	3	1	1	1	7	**Minor Challenge**
14. Time Zone Gaps	1	1	1	2	1	6	**Minor Challenge**
15. Pilot Certification	1	1	1	1	1	5	**Minor Challenge**

These regulatory barriers are being pursued by the FAA and NASA on policy action and research effort respectively. However, the greatest barrier is the FAA aircraft certification process which takes years to complete proving a significant challenge for the numerous start-ups working to bring the public into a supersonic era.

III. Methodology

A. General Overview

This project will focus in completing the 3 phases of Parametric sizing, Configuration Layout, and finally Configuration Evaluation. This was initially begun with studying the giants of the past such as work done by Kelly Johnson, Mr. Sanger and many others to learn from what has been achieved, developed and already researched; recreating the wheel is a pointless task. Each of these 3 phases involves multiple interconnected disciplines ranging from Weights & Balances to Propulsion.

B. Discipline Inputs and Outputs

The following table outlines the inputs and outputs for each discipline of the team.

N2 Diagram by: Ariel Almaraz	Outputs ↓								
	Propulsion		Safety Requirements, Budget				Vehicle Dimensions and Shapes		
	Exhaust Heat	Aerothermodynamics	Safety Requirements, Budget	Initial Dynamic Pressure and Trajectory, Atmospheric Properties and Mach Speed	Vehicle Protection Requirements	Velocity and Pressure Approximations	Vehicle Dimensions and Shapes	Control Surface Sizing Ratios, Thrust Angles	Weight limits for TPS
	Engine Cost, Fuel Cost	TPS Solution Properties	Cost & Certifications	Fuel Fraction	Seat number		Stuctural Materials	Flight Computers	Component List
	Thrust, Specific Impulse, Mass Flowrate	Dynamic Pressure Limits	Safety Requirements, Budget	Performance & Trajectory	Planform Area, TOGW	L/D		Stability & Control derivatives	
Inputs →	Engine Weight & Volume, Thrust-to-Weight, Propellant		Overall Project Cost, ROI, Certification Requirements, Budget	Fuel Fraction	Synthesis	Take-off and Landing Requirements	Wetted-to-Planform Area, Structural Index		Systems, Crew/Passenger, Weights & Volumes
		Allowable wing/VT thickness	Safety Requirements, Budget		Planform Area	Aerodynamics	Length of Vehicle	Control Surface Sizing Ratios, Thrust Angles	
	Engine Dimensions	TPS Solution Thicknesses	ROI, Cost per Seat, Safety requirements, Budget		Planform Area	Airfoil shape, planform shape, fuselage shape	Geometry & Structures	Control Surface Sizing Ratios	Recommendations for Internal Layout, Component List
	Thrust Vector and location		Safety Requirements, Budget			Aerodynamic coefficients, Location of Life, NP and AC	Vehicle Dimensions and Shapes	Stability & Control	CG locations, Moments of Inertia
	Mass Flow Rate of Engine, No. of Engines	TPS Weights, Materials and Densities	ROI, Cost per Seat, Budget	Fuel Percentages at each Phase of Flight	General Vehicle Parameters		Current Layout, General Geometry dimensions	Control Surface Sizing Ratios	Weights & Balances

Fig. 41 N2 Diagram of Inputs and Outputs [46]

C. Parametric Sizing

The Parametric Sizing phase of this project is based on Hypersonic Convergence; this methodology is semi-empirically based using reference aircraft in the supersonic and hypersonic speed regimes as the "building blocks" of the vehicle sizing process. However, the main drivers in this design phase are inputs from the Trajectory, Propulsion, and W&B disciplines. To achieve these ends various assumptions were made of the vehicles Fenix is generating in this phase of the design process.

Assumptions

Geometry Discipline – Gross Configuration

a. Blended Body (trades for Wing Body, All Body)
b. Tail-aft (trades for Tail-first, Three-Surface, Flying Wing)
c. Relation of slenderness ratio to wetted area to planform area ratio

Propulsion Discipline – Systems

a. Engine Specifications (Volume, Flow Path, Thrust, Fuel Consumption)
b. Combined Cycle Design (Mach number at transitions)
c. Rocket Engine (oxidizer-to-fuel-ratio)

W&B Discipline – Weight & Volume constraints

a. Mission Requirements (Systems Weights & Volumes)

b. Crew & Passenger coefficients

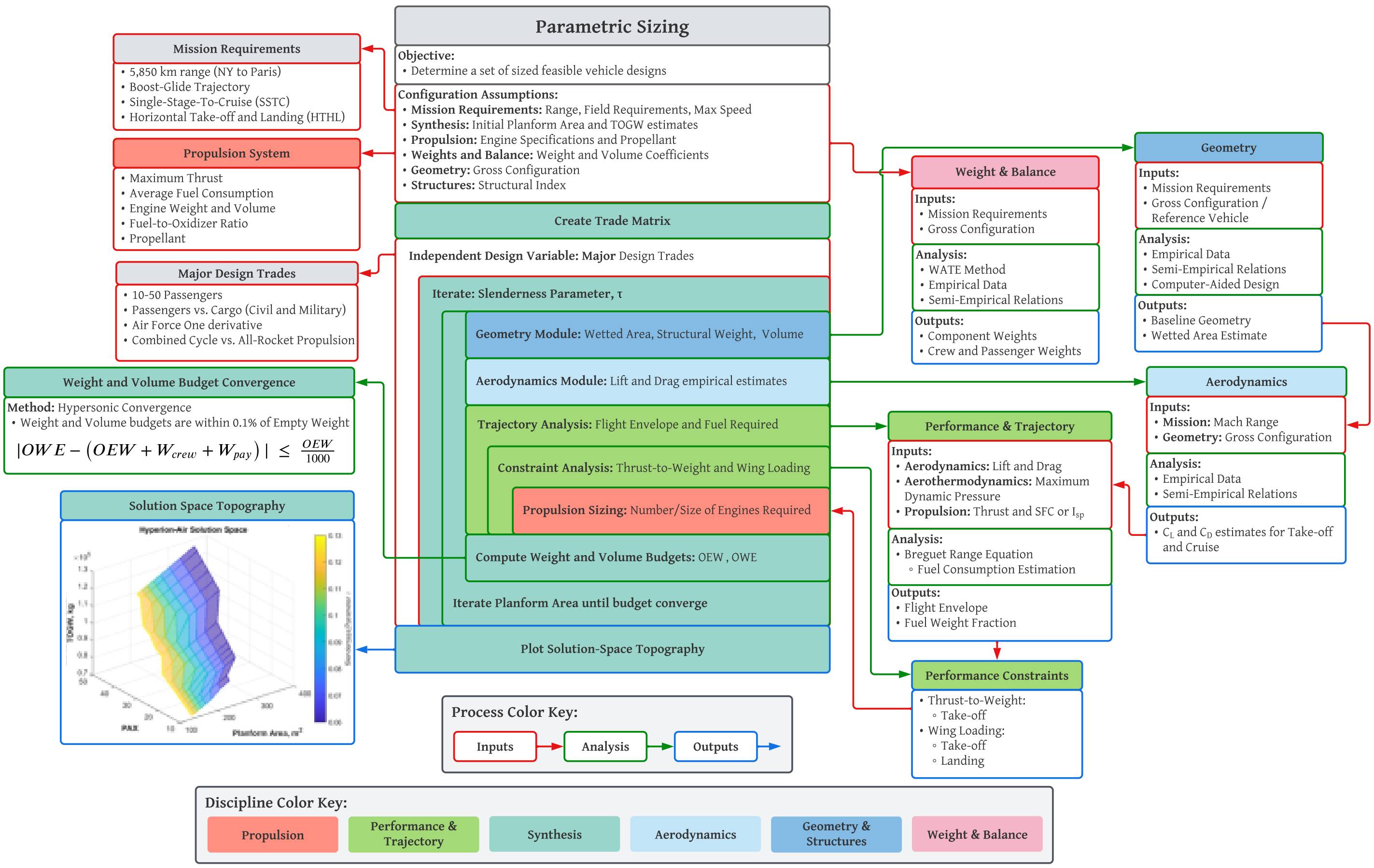


Fig. 42 Parametric Sizing MDA (MDA1)

The various modules are explained above in MDA 1 in how they fit together into the iterative process. The result of the Parametric Sizing phase of the design process is a carpet plot of design vehicles that can perform the mission, the remaining phases of Configuration Layout and Configuration Evaluation are used to fully develop the vehicles within the solution space and assess said vehicles respectively. The goal of all three phases lay in selecting the lightest and most profitable vehicle that can perform the mission given.

Despite being a robust method, it must be recognized the volume budget considers the volume as a “liquid volume” thus assuming all components are able to fill the vehicle in volume but not necessarily in dimensions, this is mitigated by the inclusion of a “void-volume” parameter which serves as additional volume of “empty space” and is a function of the total volume of the design point. The Configuration Layout phase will remove a vehicle from the design space if all necessary components are unable to be placed inside the vehicle geometry without retaining an adequate aerodynamic shape (and thus aerodynamic performance). In the case of all designs being deemed non-feasible by the Configuration Layout phase the Parametric Sizing phase will be redone with adjusted input parameters. This situation may arise due to attempting to size a vehicle ahead of current industry capabilities such as materials, or propulsion systems as this project is designed to be a “near-term” endeavor rather than requiring years of involved research and development (R&D) to achieve due to the commercial nature of the Fenix program.

D.Configuration Layout

The 2nd phase of the conceptual design process known as Configuration Layout, essentially further develops the solution space of vehicles generated in the Parametric Sizing phase such as providing quantified dimensions both externally and internally. All components necessary to evaluate each vehicle in the final phase are constructed here; most of this phase relies on the Geometry and W&B disciplines. The MDA process for this phase is blueprinted in the following Nassi-Shneiderman diagram.

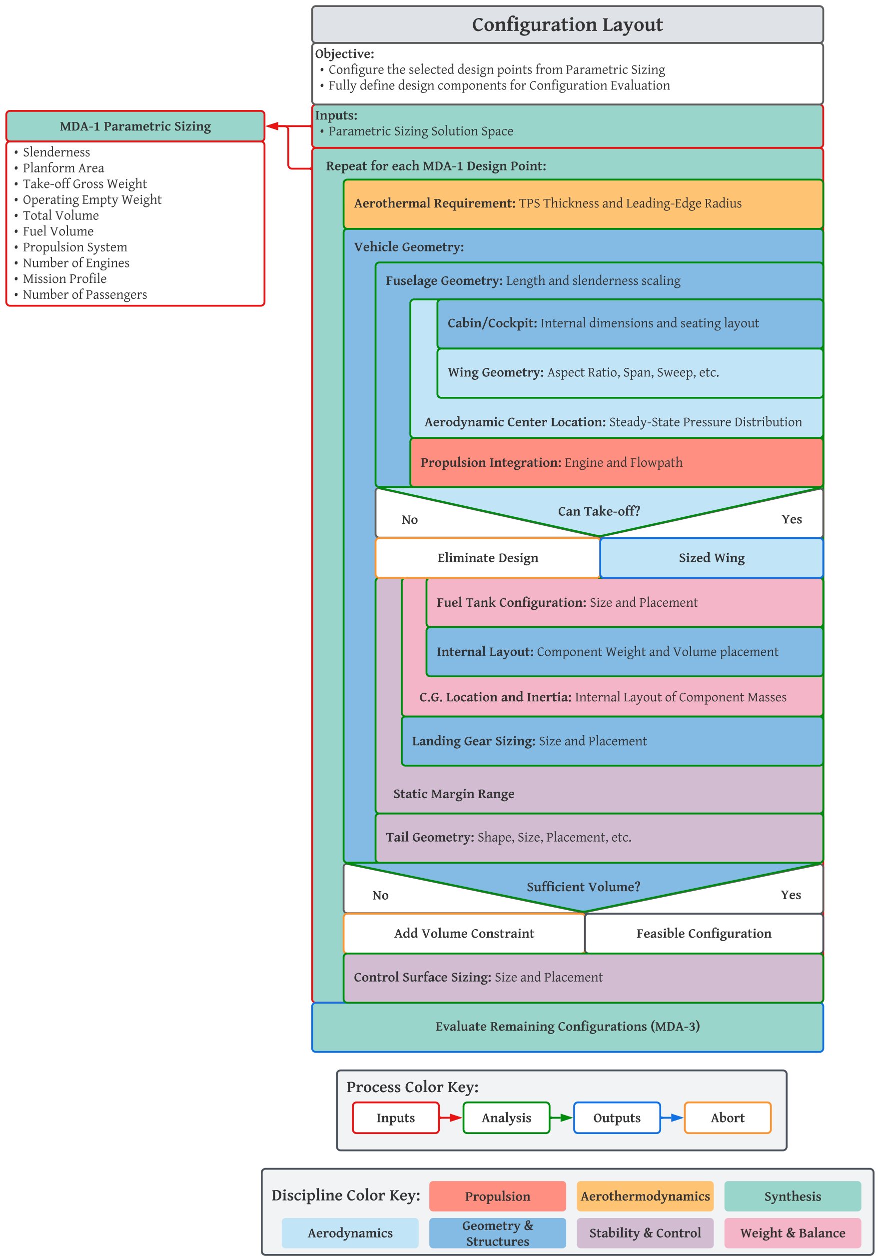


Fig. 43 Configuration Layout MDA (MDA2)

Sizing data is passed on to the Configuration Layout phase from the Parametric Sizing phase relating to the:): take-off weight, empty weight, structural weight, planform area, slenderness, total volume, propellant volume, number of engines, size of engines, and mission profile/trajectory. The process begins with the Aerothermodynamics discipline assessing the vehicle and providing a required TPS thickness and Leading-Edge radius to account for the heating loads present in the mission profile. Next the Geometry discipline uses non-dimensionalized characteristics to size the planform and an ogive wing design optimized for the mission profile providing: Aspect ratio, taper ratio, leading-and/or trailing-edge sweep angles, and a normalized airfoil shape. Due to using the Sänger EHTV as the reference vehicle for the Fenix program the planform is a double delta with a trailing-edge sweep while the point where the wing "starts" on the fuselage is kept variable. In designing the wing and planform to conform to the planform area given by the Parametric Sizing phase the Geometry discipline determines the volume of the wing of which is used to determine the remaining volume allocation to the approximate "fuselage".

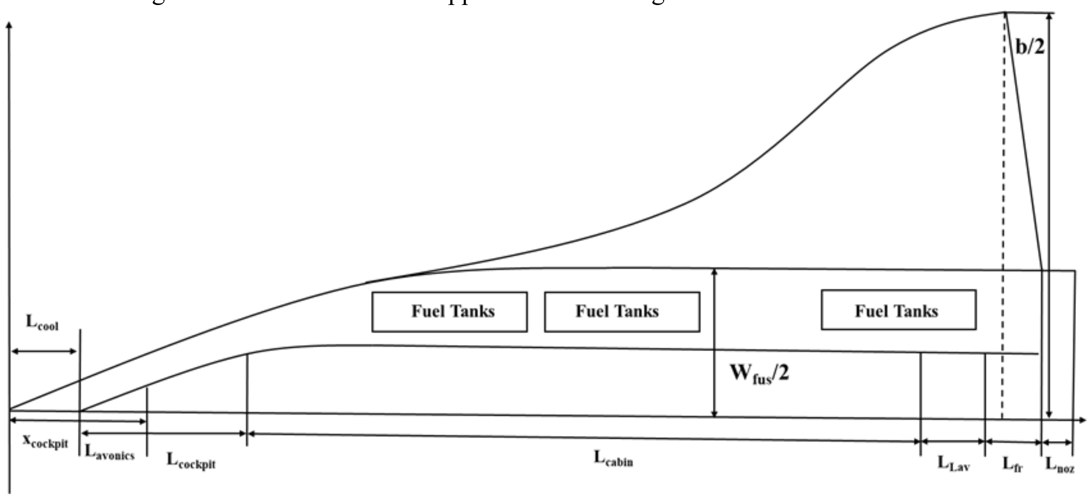


Fig. 44 Parameterization of Planform [4]

The fuselage is scaled accordingly to occupy the remaining volume budget while still accommodating the crew and passengers. As such the fuselage section is parameterized around the cabin and cockpit seen above in Fig. 44; the cabin is split into two sections the upper and lower where passengers and luggage will reside respectively as seen in Fig. 45 below. The "dividing line" between the passenger cabin and luggage area where the floor will be located is decided by the set desired aisle height of which is a trade between being able to stand up fully in the aisle or how much "crouching" is required for the average customer height.

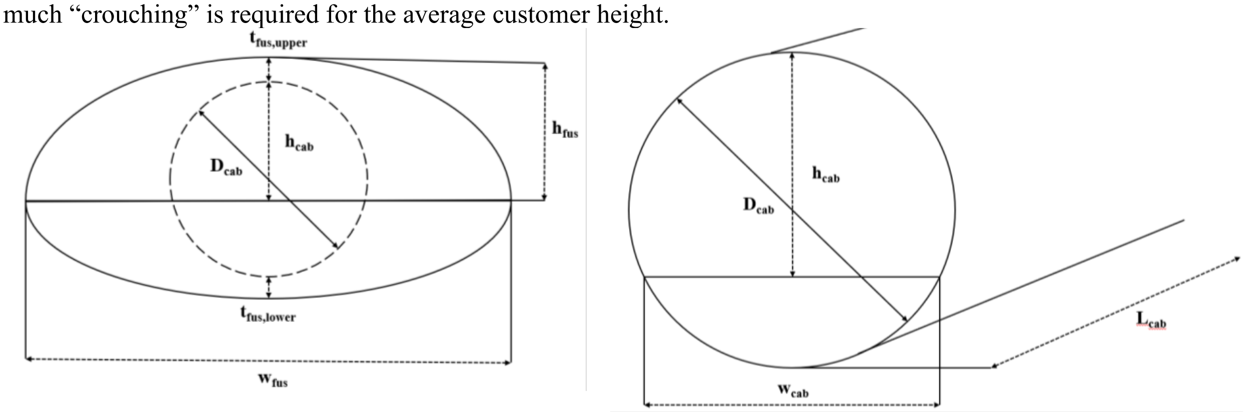


Fig. 45 Parameterization of Fuselage and Cabin [4]

With the general layout of the geometry complete the Aerodynamics discipline determines the aerodynamic center (AC) of the vehicle with the objective of keeping the center of gravity (CG) as close to the AC as possible or slightly aft to the AC and colinear to the center of thrust to mitigate instabilities in the design. Said CG is determined by the Weights & Balances discipline once the propulsion system inlet is sized and placed on the vehicle.

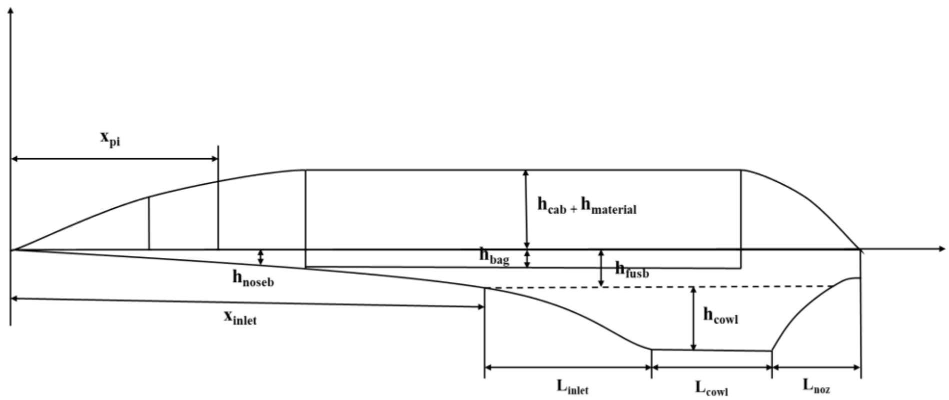


Fig. 46 Parameterization Side-View Propulsion System [4]

Additionally, the Weights & Balances discipline determines a CG shift range possible for each configuration. This is due to the fuel tanks contributing slightly over half the Take-Off Gross Weight of which can hinder the stability of the vehicle during the mission's trajectory due to fuel burn. To mitigate these adverse effects multiple smaller tanks are used for the fuel around the vehicle to facilitate the pumping of fuel to different areas to shift the CG into a more favorable position thus providing a range of static margins to the Stability & Control discipline. If the static margins are not favorable, then the MDA-2 process is reiterated adjusting the AC or CG locations by changing the internal layout. On the other hand, if the dimensions/volumes of the components do not fit within the vehicle design then the process returns to MDA-1 with a volume constraint. If everything checks out regarding the safety, stable yet maneuverable, volume allocation works, and everything is up to certification requirements the design is saved and sent to Configuration Evaluation.

E. Configuration Evaluation

The final phase of the conceptual design process is Configuration Evaluation which encompasses all the disciplines to analyze and constrain the developed aircraft created from the Configuration Layout to answer questions such as: Is the configuration capable of completing the mission? If more than one trade can complete the mission, which one does it best? After the mission is complete, what is the turnaround time to fly again and how will that affect the ROI? Can the Configuration Layout be done more effectively now that there is a better picture of the final design? This will require an immense amount of back and forth between each discipline's programs and iterative procedures to zero in on the best designs. Unique to this phase, each design will be evaluated for each 5 phases of flight: horizontal take off, climb, cruise, descend and horizontal landing seen in the below Nassi-Shneiderman diagram.

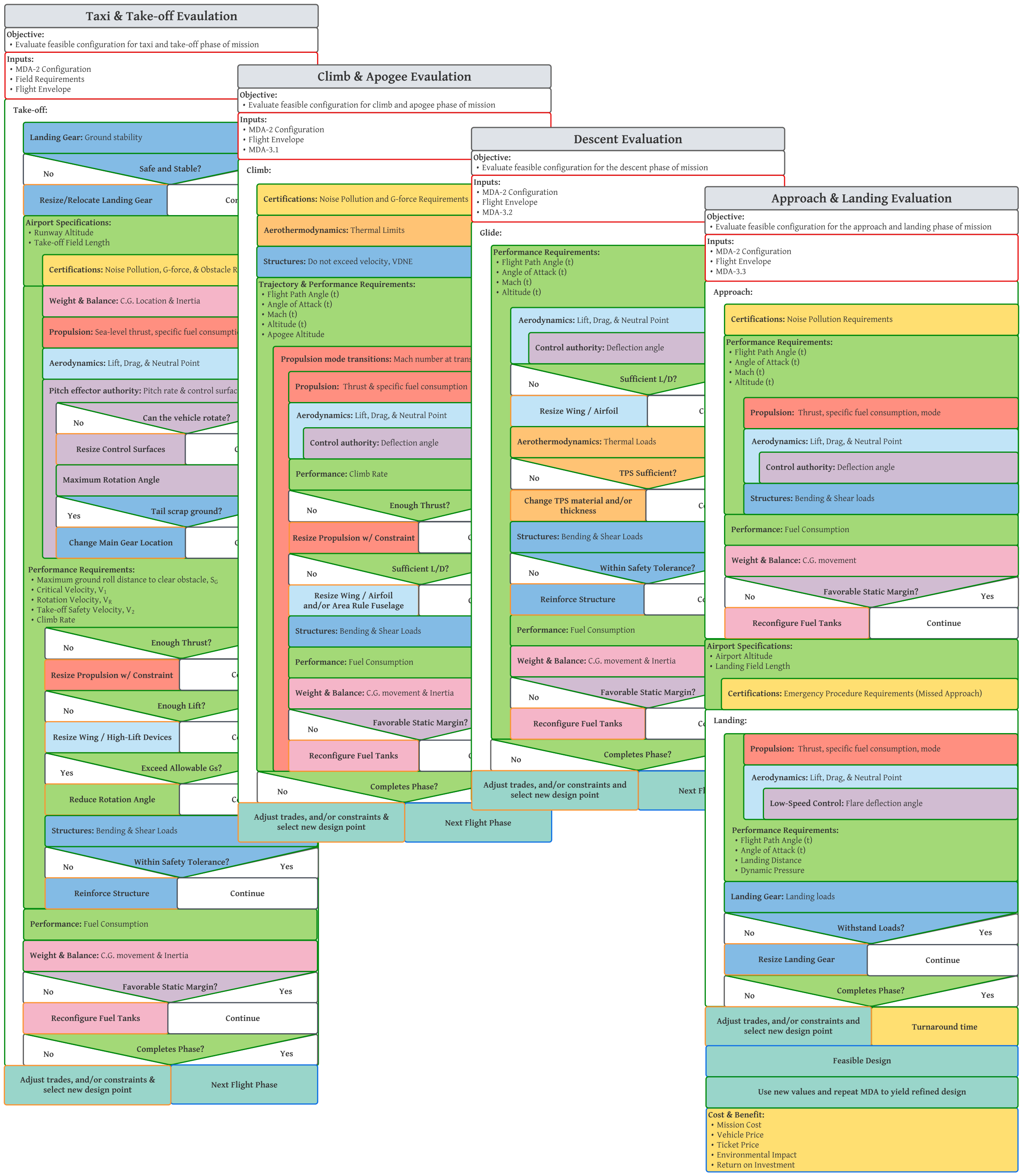


Fig. 47 Configuration Evaluation MDA (MDA3)

IV. Weights – Balances

A. Understanding the Discipline

Most of the results of the Weights and Balances discipline will be involved in the Parametric sizing and Configuration Layout phases of conceptual design.

- **Purpose**: Create a weight breakdown of vehicle, determine vehicle CG for Stability discipline, provide component list and recommend internal layouts for the Geometry discipline.
- **Outputs**: Primarily Geometry, Synthesis, Stability & Control
  - Geometry: Component list with weights, feedback to internal layout and provide recommendations
  - S&C: CG and moment of inertia determinations for vehicular stability
  - Synthesis: preliminary sizing weight estimates (systems, crew/passengers, weights, and volumes)
  - Cost: Component list and specifications
  - Aerothermodynamics: Weight limits for TPS and material recommendation
- **Inputs**: Primarily Geometry, Synthesis, Performance & Trajectory
  - Geometry: Internal and External layout, vehicle dimensions
  - Synthesis: General vehicle parameters
  - P&T: Fuel percentages at each flight phase
  - S&C: Control surface sizing ratios
  - Cost: ROI, Cost per Seat, Budget
  - Aerothermodynamics: TPS thickness, weight, and density
  - Propulsion: Mass flow rate of engine, No. of engines

B. WBS IDA

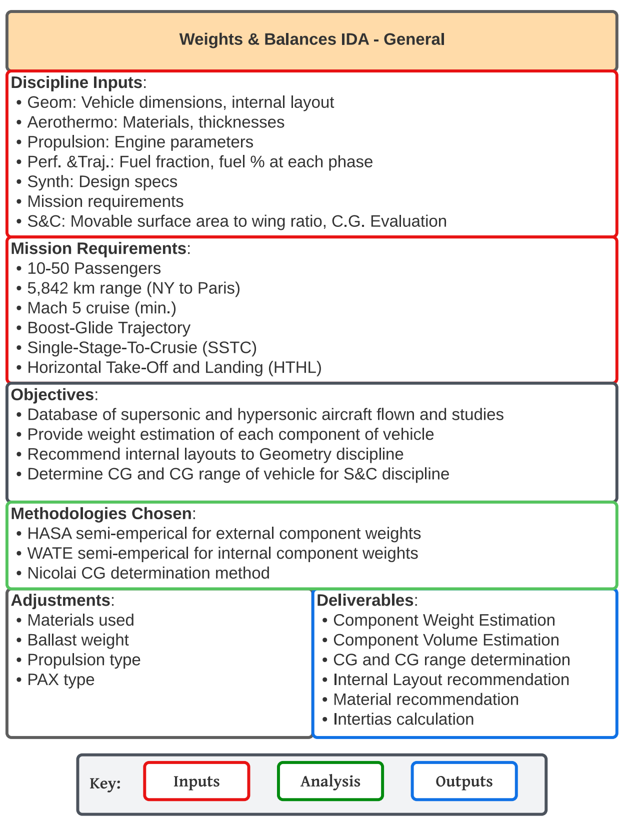


Fig. 48 W&B General IDA

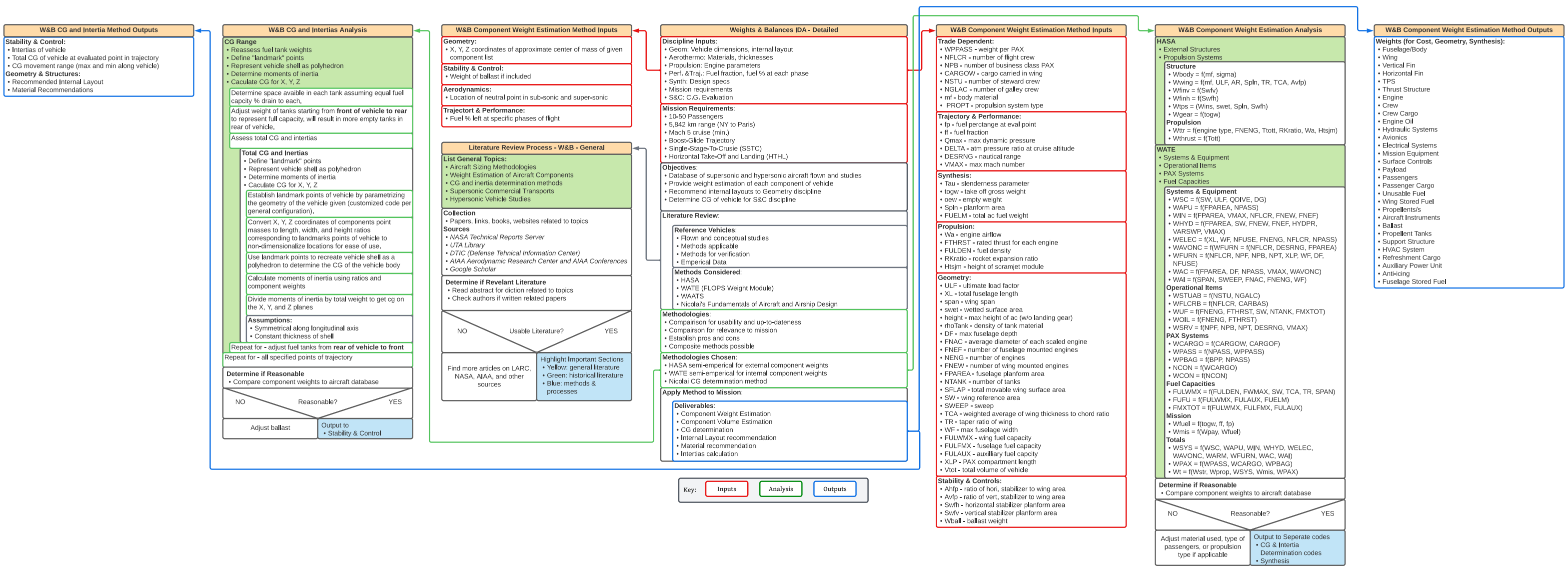


Fig. 49 W&B Full IDA

C.Work Breakdown Structure

Table 9 Weights and Balance Discipline Structure and Roles

Member	Objectives	Deliverables
Discpline Lead: Roman Renazco	Develop robust CG and weight determination method	MATLAB Methodolgies
Ariel Almaraz	Discipline Verification	Verify methods and Organize Outputs
Michael Hoofard	Build method for CG change due to fuel burn	CG fuel burn adjustment

As the discipline lead of the Weights and Balance discipline, the author will organize the discipline with the lead as the main programmer and the other members serving as support in method and vehicle verification as well as developing a reliable method to adjust weight and CG of a vehicle for fuel burn.

By the end of the semester, the Weights and Balance discipline will have generated a program capable for RBCC, all-rocket cruise, SSTO, Air Force One, PAX civil transport, PAX military transport, cargo civil transport, and cargo military transport vehicle designs to determine the weights, inertias, and CG range of these various trade studies.

D.Discipline MATLAB Functions

Thus far HASA has been coded and WATE has been integrated into HASA for more accurate weight estimation and breakdown as HASA is quite old and lacks the inclusion of PAX systems in its breakdown. See Fig. 51 for greater detail.

E.Methodologies

1. *C.G. Determination:*

The CG determination is achieved by considering each component of the vehicle as a point mass with X, Y, Z coordinates for each given by the Geometry discipline, however a different approach will be taken for the body and wing of the vehicle in "3D graphing" the shell of the vehicle as a polyhedron using, and the distances of each component from "landmark points" of the vehicle will be converted to ratios. Next the ratios and weights will be used to determine moments of inertias (with the assumption of z-axial symmetry) and finally used to determine the true CG of the entire vehicle; this is seen in the following method IDA.

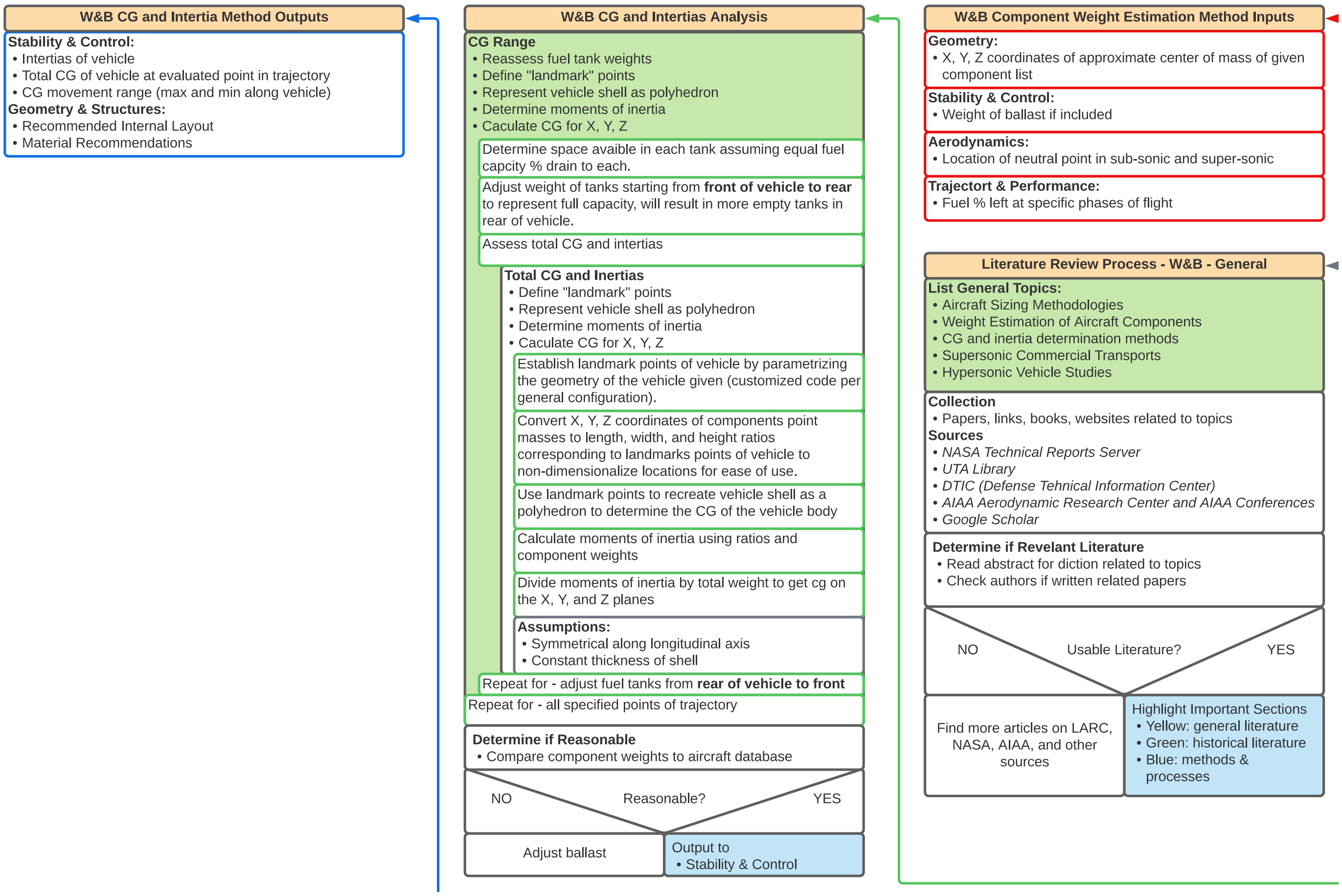


Fig. 50 W&B CG and Inertias Method IDA

A CG shift range is determined for each vehicle at a given point in the trajectory of the mission, the CG is shifted by pumping fuel to different tanks in the vehicle. The range is determined by filling all fuel tanks from front to rear of the vehicle with the available fuel and determining the total CG and inertia of the vehicle; this is repeated by filling all fuel tanks from rear to the front of the vehicle with the available fuel. Said available fuel is determined by the point in the trajectory in how much fuel is left in the vehicle.

2. *Component Weight Estimations*

The weight estimation is split into the external and internal components, the former consists of propulsion systems and structures and latter consists of weapon systems, systems and equipment, operation items, PAX systems, fuel capacities all of which culminate to yield the total vehicle weight.

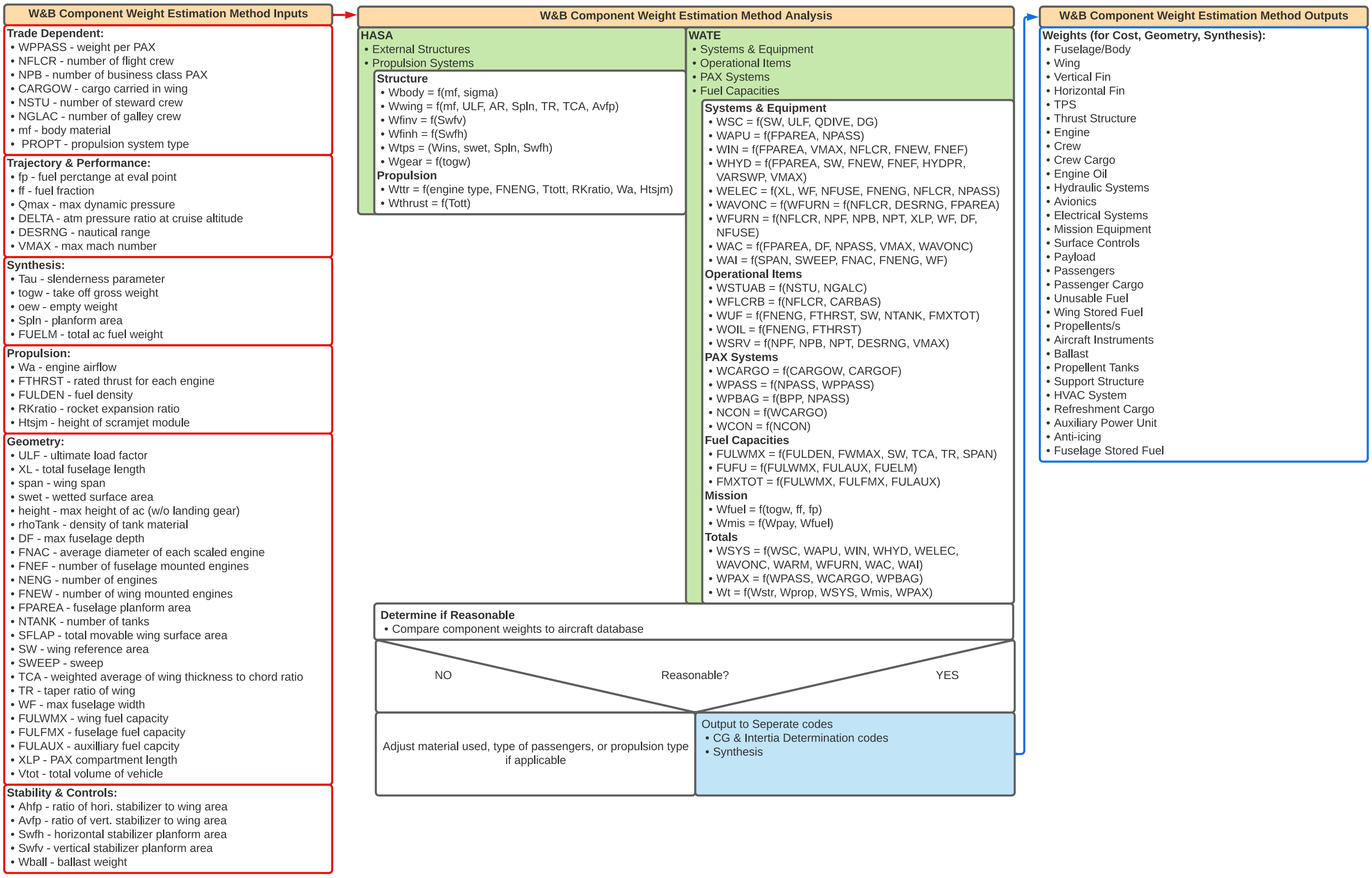


Fig. 51 W&B Weight Estimation IDA

The components of the base vehicle are split as follows:

- Fuselage/Body
- Wing
- Vertical Fin
- Horizontal Fin
- TPS
- Thrust Structure
- Engine
- Crew
- Crew Cargo
- Engine Oil
- Hydraulic
- Avionics
- Electrical Systems
- Equipment
- Surface Controls
- Payload
- Passengers
- Passenger Cargo
- Unusable Fuel
- Wing Stored Fuel
- Propellent/s
- Aircraft Instruments
- Ballast
- Propellent tanks
- Support Structure
- HVAC System
- Refreshment Cargo
- AUX power unit
- Anti-Icing
- Fuselage Stored Fuel

These components are the internals of the vehicle based on WATE and HASA: [22]

The following constitute the inputs from each discipline concerning the component weight estimation code created by the weight and balances discipline, primarily this is based on the semi-empirical equations of HASA for the external components and WATE for the internal components. Said equations are seen previously in the Literature Review section.

Geometry

- Ultimate Load Factor
- Total Fuselage Length
- Wingspan
- Wetted Area of Aircraft
- Max height of Aircraft
- Material of fuel tanks
- Average diameter of engine
- Fuselage mounted engines
- Maximum total fuel
- Total volume of vehicle
- Wing mounted engines
- Total number of engines
- Fuselage planform area
- Number of fuel tanks
- Movable wing surface area
- Reference wing area
- Quarter chord sweep angle of wing
- Length of passenger compartment
- Weighted Avg. of wing thickness to chord ratio
- Taper ratio of wing
- Maximum fuselage width
- Maximum fuselage deth
- Fuel capacity of Fuselage
- Fuel capacity of Wing
- Auxiliary fuel tank capacity

Stability & Control

- Ratio of horizontal stabilizer area to wing area
- Horizontal stabilizer planform area
- Ratio of vertical stabilizer area to wing area
- Vertical stabilizer planform area
- Weight of ballast

Propulsion

- Engine Airflow
- Rated thrust for each engine
- Rocket expansion ratio
- Height of scramjet module
- Fuel density ratio for alternate fuels
- Engine type

Synthesis

- Tau
- TOGW
- OEW
- Spln (planform area)
- DGW (design gross weight)
- Ramp weight
- Total aircraft fuel weight

Trajectory & Performance

- Fuel Percentage at point
- Fuel fraction
- Maximum dynamic pressure
- Nautical range
- Atm pressure ratio at cruise altitude
- Max Mach number

Aerothermodynamics

- Thermal Protection weight per area

Trade Dependent

- Weight per passenger
- Number of flight crew
- Number of business class
- Cargo other than PAX bags
- Cargo carried in wing
- Carrier take off toggle
- Number of galley crew
- Number of steward crew

3. Component Placement

With most of the Geometry virtually clueless on where to put components the W&B discipline stepped up to provide recommendations on the placement of each component, most importantly the fuel tanks which were vital in aligning the CG of the aircraft with the neutral point at the various phases of flight by pumping the fuel around.

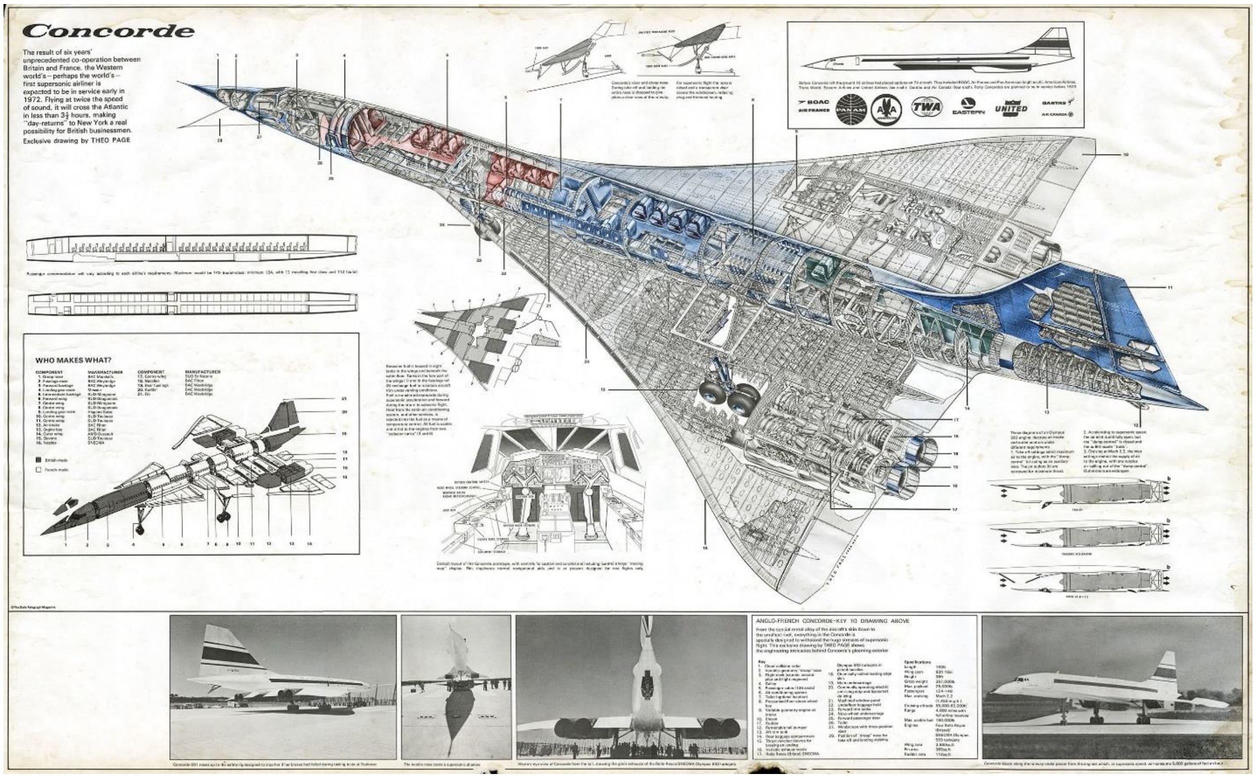


Fig. 52 Concorde Cutaway [10]

The non-fuel components of the vehicle will primarily use the Concorde as a basis on where to position the items as point masses to determine the CG and thus manage the stability of the aircraft.

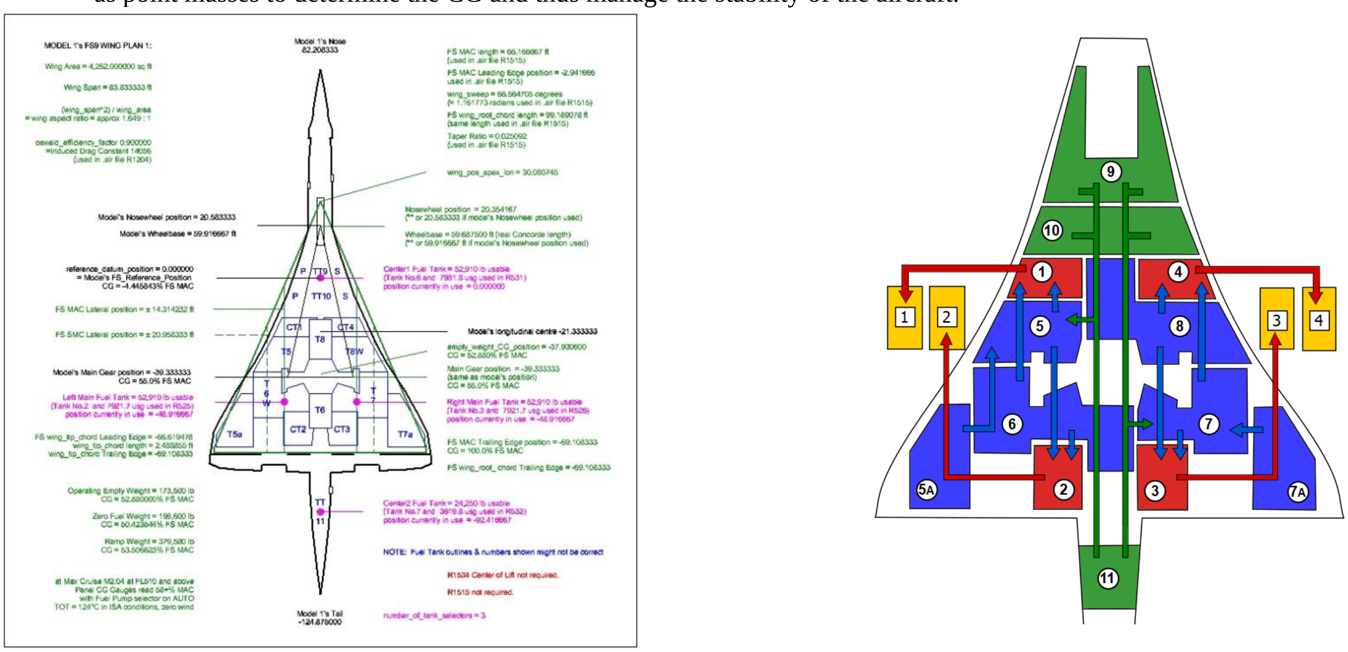


Fig. 53 Concorde Internal Tank Layout [10]

Initially, the internal layout of tanks was like that of the Concorde as seen on the right and left respectively as the placement of the propulsion systems was unknown yet, however with the cementing of the decision of having all the engines under the fuselage tanks 1 through 4 will output to the under carriage of the fuselage instead of the wings. Most of the fuel is kept in the wing sections of which have markedly great volume percentages than the Concorde due to the area ruling of the Fenix program aircraft. The internal layout is initially set in the CL phase and refined in the CE phase to optimize the CG shifting maneuver.

F. Verification

The verification of the built methodology for team Fenix will be verified using detailed weight breakdowns derived from re-creating the Concorde and Tupolev Tu-144 LL in FLOPS from scratch. To achieve a greater degree of accuracy the more data on each aircraft the better estimate. The data derived using FLOPS to generate and assess said vehicles spans a wide range of disciplines, 3 different ways of FLOPS use are possible: analysis, parametric variation, and optimization; in the case of the W&B discipline the focus will be on the analysis configuration of FLOPS, see Supersonic Transport FLOPS Optimization in Appendix H: Raw Data Output for a generated general supersonic transport optimization input and detailed results. It has been found an engine deck is preferred for a more accurate trajectory and mission performance in FLOPS, however, such an engine deck has yet to be found for Concordes Olympus 593 Mrk610 turbojet powerplants.

Seen in Appendix D: W&B Detailed Verification Results → Section A is an approximate weight breakdown using FLOPS to essentially 'recreate' the Concorde; this generation of the Concorde lacks an appropriate engine deck used, as such only an analysis of the weights and aerodynamic qualities of the Concorde have been realized seen in Appendix H: Raw Data Output → Section B. This is used to compare the capabilities of the weight estimation code with inputs from the Synthesis and Geometry disciplines. The detailed results of the W&B weight estimation are also seen in Appendix D: W&B Detailed Verification Results → Section A. By recreating a weight breakdown using the W&B component weight estimation code, and weight breakdown and total weight were calculated for the Concorde, this was compared to the weight breakdown of the Concorde using FLOPS with an approximate error of **1.83 %.**

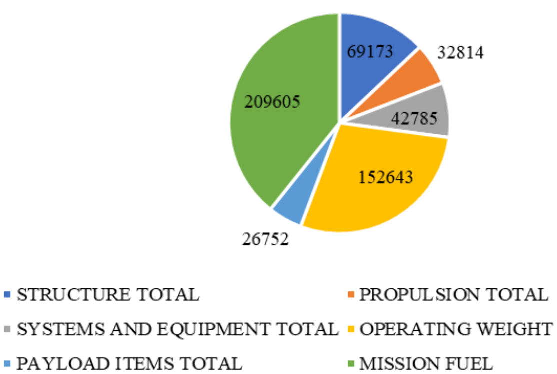


Fig. 54 FLOPS Concorde Weight Pie

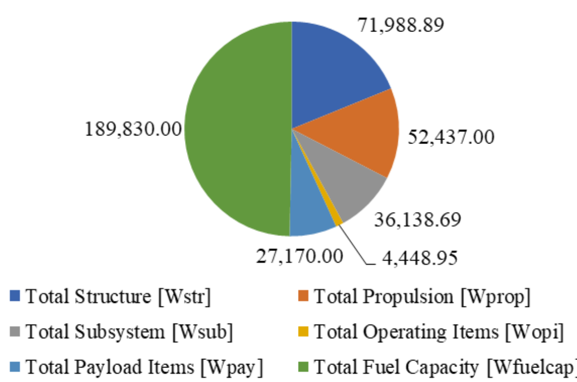


Fig. 55 W&B Concorde Weight Pie

Similarly, the Tupolev Tu-144 LL aircraft has been generated by FLOPS to create more verification for the W&B discipline, thus creating the detailed weight breakdown of the Tu-144 LL. The results of FLOPS and the W&B method are seen in Appendix D: W&B Detailed Verification Results → Section B.

The W&B code was unable to reproduce the Tu-144 LL aircraft perfectly due to a lack of data on the engine airflow and wing/fuselage fuel tank max volumes, as such empirical estimations have been made using ratios via the Concorde; a similar aircraft in design and used as the inspiration to the Tu-144 aircraft series.

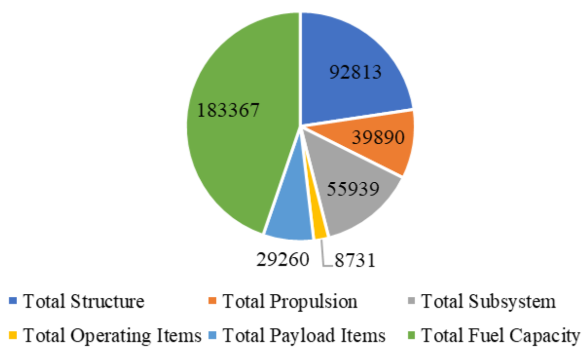


Fig. 56 FLOPS Tu-144 LL Weight Pie

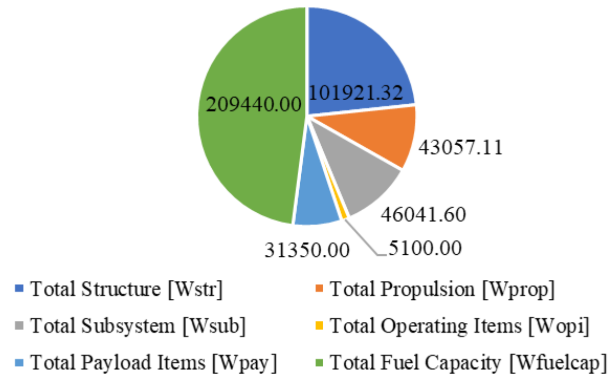
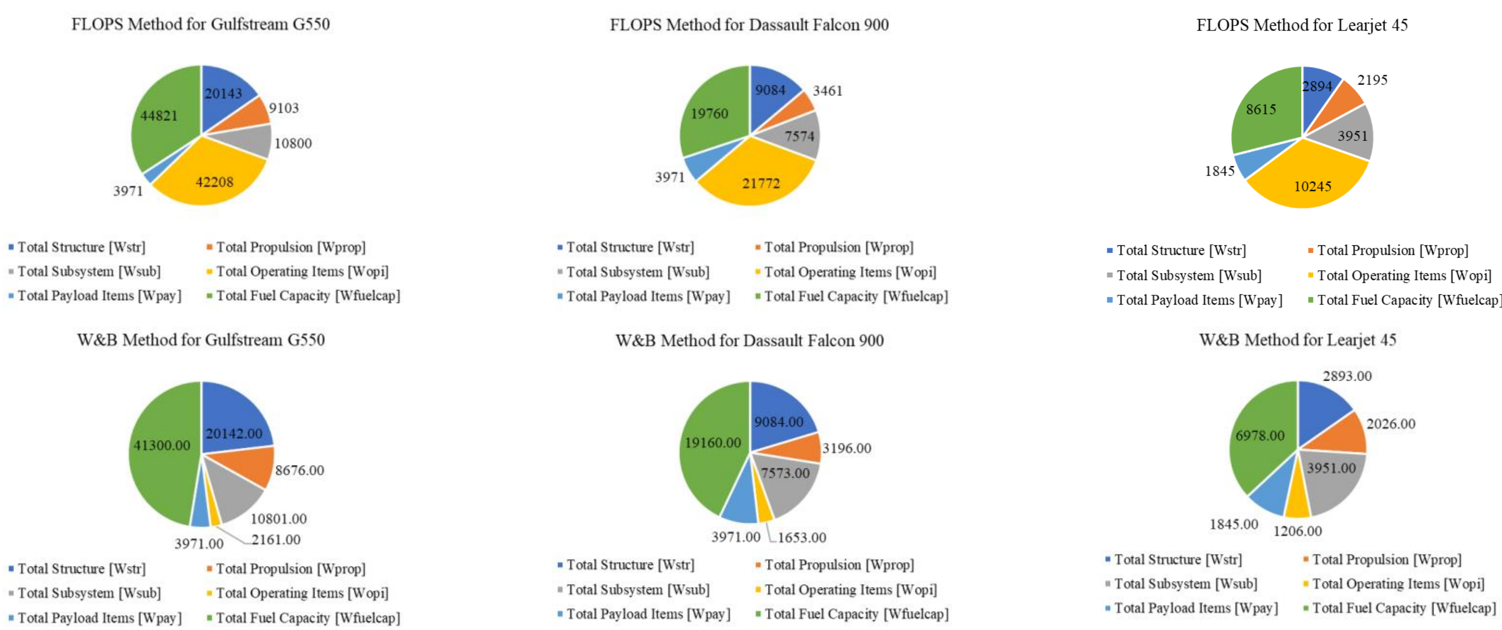


Fig. 57 W&B Tu-144 LL Weight Pie

With the error of the W&B Method being **1.82 %** and **6.16 %** for the Concorde and Tu-144 LL crafts respectively it has been confidently proven the capability of the W&B Method being up to the task for the Fenix program.

Further verification has been made for Gulfstreams G550, Dassault Systems Falcon 900, and the Learjet 45. The resulting component breakdown pie charts and percent errors are shown below with further details seen in the Appendix. See the Aircraft Database section for the data used in FLOPS and the W&B component estimation codes.



Error Discrepency: **4.45 %** Error Discrepency: **1.93 %** Error Discrepency: **13.76 %**

Fig. 58 W&B Verification for G550, Falcon 900, Learjet 45

G. Results

The internal layout of the vehicle has been set by the author after extensive analysis of other aircraft internal layouts and back-and-forth with the Stability & Control Discipline. During take-off the internal layout enables the CG to be shifted back to the location of the main landing gear as soon as the wheels were no longer touching the ground, this maintains the same point of rotation otherwise there would be a sudden change in altitude. This is achieved by having 4.5 % of empty tank volume at take-off. See the below figure for a visual of this effect.

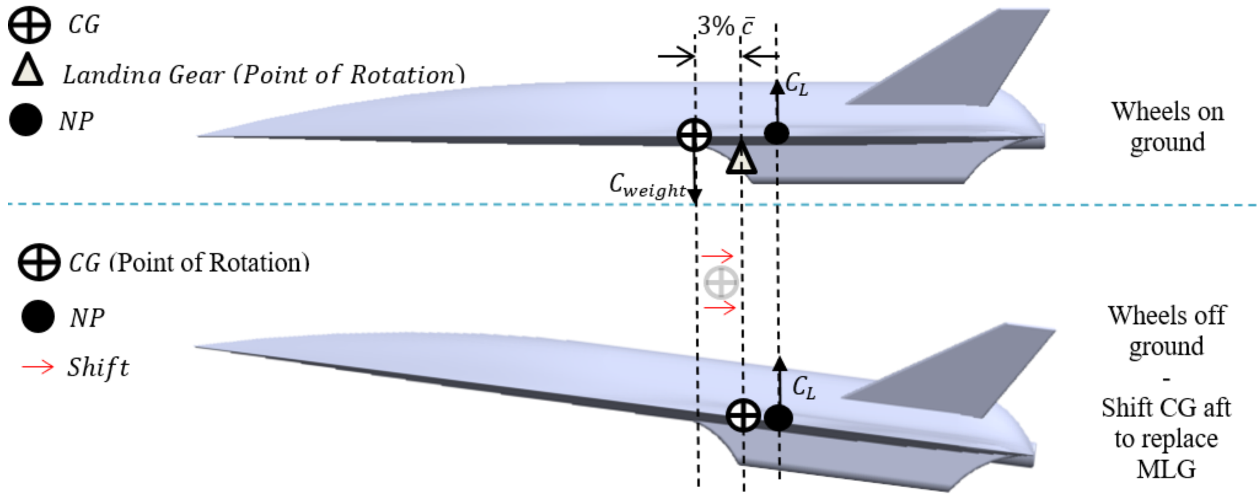


Fig. 59 CG & Main Landing Gear Relationship

Said internal layout has the CG slightly fore of the sub-sonic neutral point of the aircraft which has be found to lay at **51.84 %** of the length of the aircraft at take-off. Additionally, at the start of the sonic dash phase of flight the aircraft layout has enabled the CG to lay at the supersonic neutral point found to lay at **62.85 %** of the vehicle length. This is only possible due to the fuel remaining is at **86.66 %** being shifted to move the CG at this point of the trajectory. Lastly, the aircraft is just slightly stable in its sub-sonic landing at approximately 1**0 %** fuel remaining due to the internal layout of an operating weight empty aircraft CG being designed at just fore the sub-sonic CG. The following table represents the components placements in terms of ratios of the height and length of the vehicle. Note this is for the CL phase of the conceptual design process and will differ in the final results after the CE phase.

Table 10 Internal Layout of Fenix Vehicles

'RgearZ'	0.03	'RgearX'	0.65	'RflcrbZ'	0.45	'RflcrbX'	0.29
'RbodyZ'	0.69	'RbodyX'	0.52	'RpbagZ'	0.33	'RpbagX'	0.36
'RwingZ'	0.40	'RwingX'	0.64	'Rtank1Z'	0.36	'Rtank1X'	0.34
'RfinvZ'	0.72	'RfinvX'	1;	'Rtank2Z'	0.36	'Rtank2X'	0.34
'RfinhZ'	0.72	'RfinhX'	1;	'Rtank3Z'	0.36	'Rtank3X'	0.57
'RtpsZ'	0.69	'RtpsX'	0.51	'Rtank4Z'	0.36	'Rtank4X'	0.57
'RthrustZ'	0.14	'RthrustX'	0.60	'Rtank5Z'	0.36	'Rtank5X'	0.69
'RttrZ'	0.03	'RttrX'	0.60	'Rtank6Z'	0.36	'Rtank6X'	0.69
'RwscZ'	0.5	'RwscX'	0.06	'Rtank7Z'	0.36	'Rtank7X'	0.77
'RwapuZ'	0.20	'RwapuX'	0.06	'Rtank8Z'	0.36	'Rtank8X'	0.77
'RwinZ'	0.75	'RwinX'	0.09	'Rtank9Z'	0.36	'Rtank9X'	0.84
'RhydZ'	0.50	'RhydX'	0.31	'Rtank10Z'	0.36	'Rtank10X'	0.84
'RelecZ'	0.50	'RelecX'	0.11	'Rtank11Z'	0.36	'Rtank11X'	0.90
'RavoncZ'	0.65	'RavoncX'	0.11	'Rtank12Z'	0.36	'Rtank12X'	0.90
'RfurnZ'	0.53	'RfurnX'	0.44	'Rtank13Z'	0.36	'Rtank13X'	0.95
'RwacZ'	0.35	'RwacX'	0.67	'RcargoZ'	0.36	'RcargoX'	0.33
'RwaiZ'	0.45	'RwaiX'	0.21	'RpassZ'	0.36	'RpassX'	0.48
'RstuabZ'	0.45	'RstuabX'	0.29	'RpayloadZ'	0.36	'RpayloadX'	0.33

The tanks have the following percentages of the total fuel, notice the total comes out to over 100 % this is to account for the lower-than-typical tank weighting being used:

Table 11 Tank Fuel Capacities as % of Total Fuel of Fenix Vehicles

Tank	Total Fuel %
1	10
2	10
3	10
4	10
5	10
6	10
7	10
8	7.25
9	5
10	5
11	7.25
12	5
13	5

The baseline vehicle for the Fenix program features a blended-wing body geometry with an Ogee wing shape tailored for the mission, additionally, an aft-body expansion ramp and fore-body compression ramp are used to support the propulsion systems. Seen below is a sample of the cabin layout for the passenger variant Hyperion.

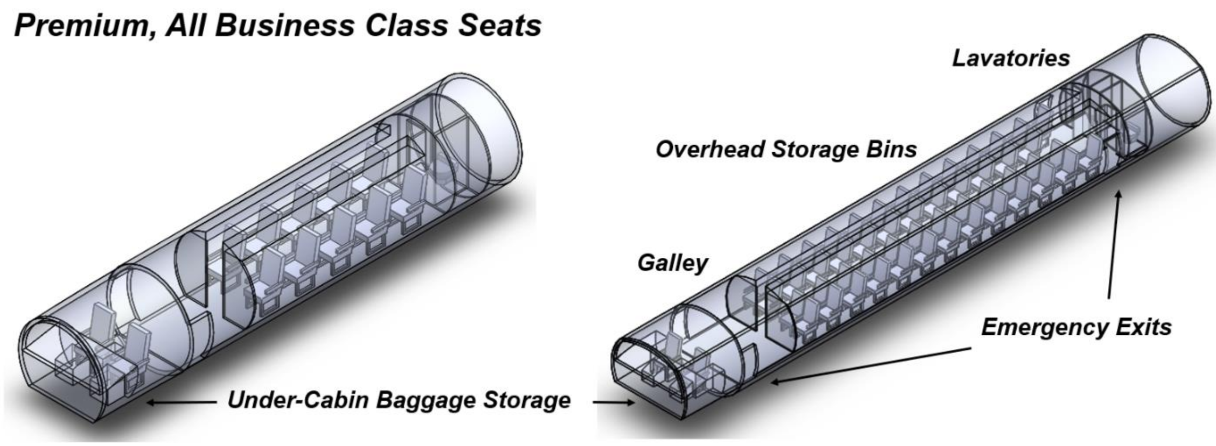


Fig. 60 Cabin Internals for 10 PAX (left) and 50 PAX (right)

The final optimal vehicles found in the Configuration Evaluation phase for the Fenix program are a 36 PAX, Tau 0.11 design for the Airbreathing design and 44 PAX, Tau 0.09 for the Rocket design. The CG shift range and the weight breakdowns for each are seen below:

Table 12 CG Shift Range for each Optimal Vehicle

36 PAX, 0.11 Tau Airbreather	CG Shift Range
Take-Off	56.65 % – 57.53 %
Subsonic Climb	56.33 % - 57.80 %

44 PAX, 0.09 Tau Rocket	CG Shift Range
Take-Off	58.42 % – 59.80 %
Subsonic Climb	57.90 % - 60.23 %

Sonic Dash	**56.03 % - 57.79 %**	**Sonic Dash**	**57.40 % - 60.66 %**
Supersonic Climb	**55.39 % - 58.05 %**	**Supersonic Climb**	**54.42 % - 58.9 %**
Glide & Landing	**56.26 % - 56.95 %**	**Glide & Landing**	**55.68 % - 56.79 %**

Fig. 61 Weight Pies for Optimal Vehicles [46]

See Appendix G: Results→W&B Optimized Vehicles Detailed Weight Breakdowns for the full detailed results.

V. Synthesis

A. Understanding the Discipline and IDAs

The Synthesis discipline mainly deals with the Parametric Sizing phase of conceptual design of the program and mapping out the 2nd and 3rd phases. To put it shortly, this involves the "magic" of formulating the initial parameters synthesized from essentially nothing but a few small general inputs from the other disciplines seen in Fig. 42. This is achieved using Hypersonic Convergence a synthesis methodology devised precisely for hypersonic vehicle design and produces a solution space of possible vehicles based on the mission profile, powerplant specifications, the gross configuration of the vehicle, weight and volume coefficients, and structural data. Additionally, the Synthesis discipline serves to create the blueprint of how the 9 disciplines interact with each other to produce a successful project, this is seen in the production of MDA 2 and MDA 3, the blueprints for Configuration Layout and Configuration Evaluation respectively. This is achieved by utilizing the IDAs of each discipline as "cogs" into the "gearbox" that runs the design process. This objective is the most important part of the Synthesis discipline, as after a well-crafted plan is made, the easier part of assembling the pieces akin to a puzzle is left.

B. Synthesis IDAs

The following figure outlines the organization of the Synthesis discipline.

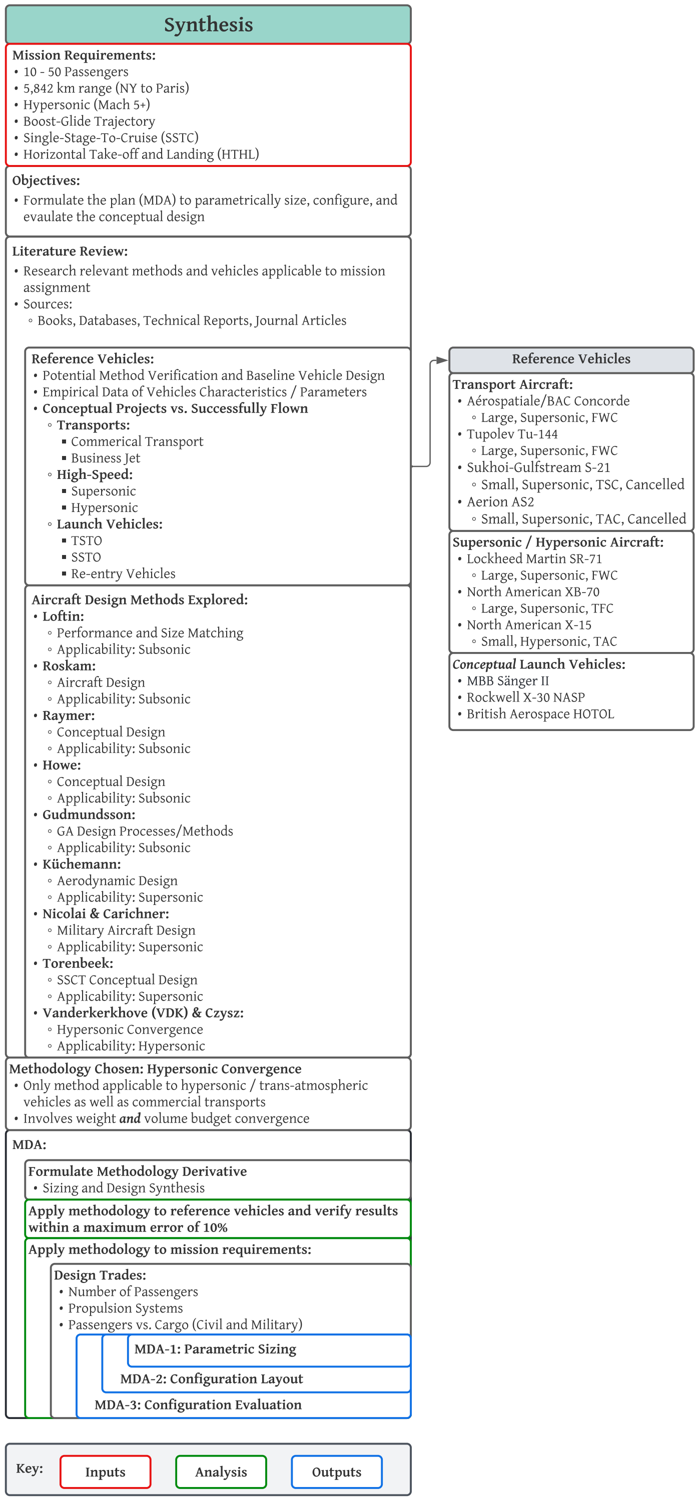


Fig. 62 Synthesis IDA

C. Work Breakdown Structure

Table 13 Synthesis Discipline Structure and Roles

Member	Objectives	Deliverables
Noah Park	Synthesis Methodology	MDA
Roman Renazco	Weight and Volume Estimation	Component Sizing
Meagan Lotz	Trajectory Analysis	Mission Profile and Fuel Estimation
Jeff Atillo	Propulsion Specifications and Trade	Propulsion Sizing

The author will assist the discipline lead, Noah Park, by feeding the Synthesis discipline with various systems and passenger/crew weight and volume for all trade studies from Air Force One to PAX and cargo for civil and military cases. The results the author will be shooting for are accurate weight and volume estimates of vehicle components for the trade studies listed in the vehicle design details above.

D. Discipline MATLAB Functions

Thus far there are 3 primary codes; one to create verification for existing supersonic aircraft, another to re-create the Sänger vehicle, and a 3rd to generate Fenix Parametric designs for the given mission parameters (which may exceed the Sänger III capabilities).

The Configuration Layout program mainly hinged on involving each discipline as a “module” in the form of functions called with data being transmitted via .xlsx files being written and overwritten. Initially, various parameters were designed as assumptions based on the Concorde as disciplines were being incorporated into the CL code processes, primarily the Geometry discipline is at the center of the process. Most of the disciplines were not iterated in the Configuration Layout only the following: Geometry, Landing Gear/Structures, Weights & Balances; where the rest of the disciplines provided static/semi-static inputs.

E. Synthesis Script: Discipline Methodology – Parametric Sizing

In short, Hypersonic Convergence has been implemented for the mission define in the project proposal. This involves various module codes each corresponding to discipline input from the Geometry, Weight & Balances, Aerodynamics, Performance & Trajectory, and Propulsion disciplines as seen in Fig. 42 i.e. MDA 1. For a more detailed explanation see Parametric Sizing.

F. Verification

To establish verification for the Synthesis methodology the Sänger EHTV has been recreated/reengineered, specifically the 8/88 EHTV due to the quantity and quality of data available. The verification of the Synthesis code build is achieved in multiple codes. The planform area of the Sänger was determined by creating a computer-aided design (CAD) model and was found to approximately be 1413.3 m^2.

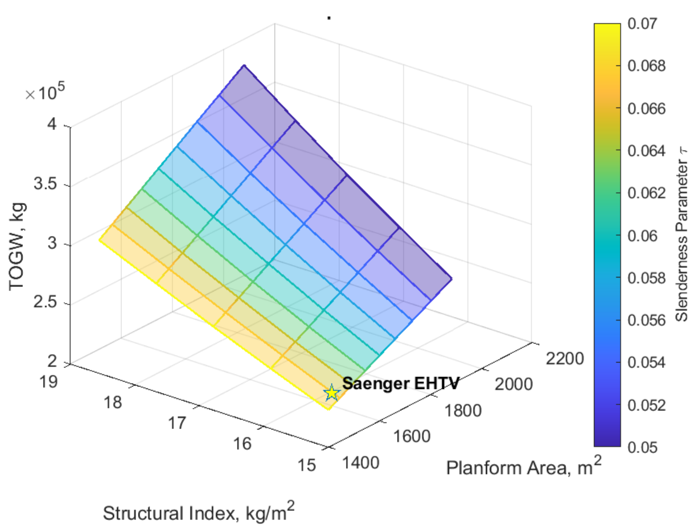


Fig. 63 Saenger EHTV on Solution Space

Table 14 Sänger Design Synthesis Parameters

Design Parameter	Input Value
Number of Crew	9
Number of Passengers	230
Engine Thrust-to-Weight	5.4
Engine Weight (kg)	3964.2
Engine Volume (m^3)	56
Fuel Density (kg/m^3)	74.63
Weight per Passenger (kg)	196
Volume per Passenger (m^3)	2
L/D ratio, max (hypersonic)	5.3
Average Cruise Specific Impulse (sec)	3650
Cruise Speed	Mach 4.4
Flight Range (km)	10,500
Cruise Altitude (km)	25
Max. Lift Coefficient	0.7
Thrust-to-Weight at Take-off	0.38

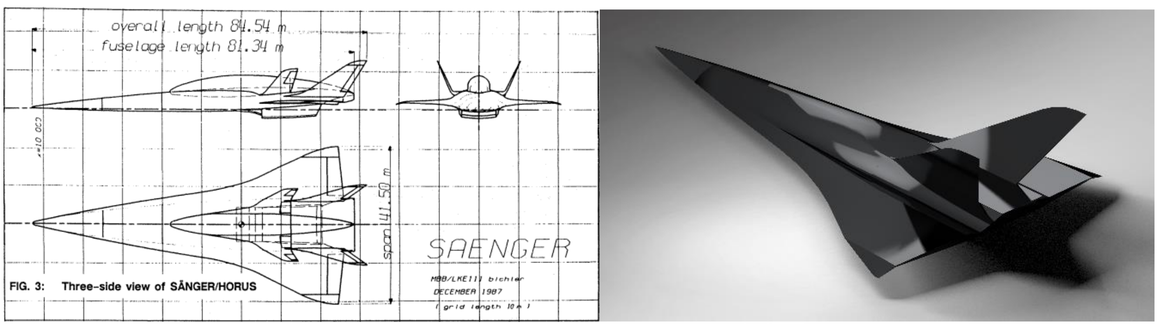


Fig. 64 Sänger II Schematic (left) [47]**, Sänger II CAD model** [4] **(right)**

The various other parameters required to "recreate" the Sänger EHTV of the 8/88 PAX version were based on the Concorde due to its similar mission specifications, regional area developed, and was used as inspiration for the Sänger series.

Table 15 Sänger EHTV Verification Results [48]

Design Parameter	Actual Value	Calculated Value	Percent Error
Slenderness	0.0578	0.065	12.457%
Take-Off Gross Weight	244,000 kg	242,370 kg	0.668%
Operating Empty Weight	149,000 kg	143,590 kg	3.628%
Planform Area	1413.3 m^2	1492.5 m^2	5.604%
Fuel Fraction	0.4098	0.407	0.688%
Number of Engines	5	5	0.00%

The next vehicles put through verification were the Concorde and Tu-144 D aircraft where both were quite in-line with the solution space generated for these supersonic aircraft as seen in the below graphic.

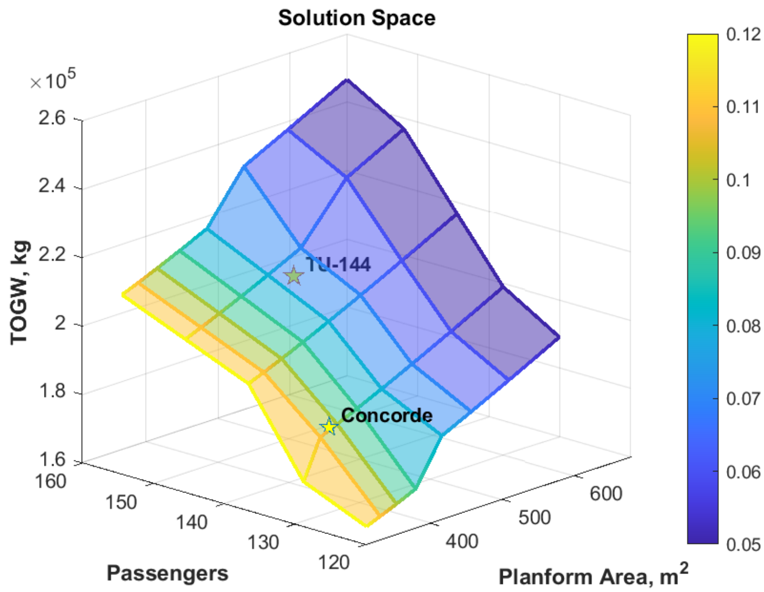


Fig. 65 Concorde & Tu-144 D Solution Space Verification

Table 16 Concorde Design Synthesis Parameters

Design Parameter	Input Value
Number of Crew	9
Number of Passengers	130
Engine Thrust-to-Weight	5.4
Engine Weight (kg)	3964.2
Engine Volume (m^3)	56
Fuel Density (kg/m^3)	74.63
Weight per Passenger (kg)	170
Volume per Passenger (m^3)	2
L/D ratio, max	7
Average Cruise Specific Impulse (sec)	3650
Cruise Speed	Mach 2
Flight Range (km)	7,250
Cruise Altitude (km)	18.2
Max. Lift Coefficient	0.7
Thrust-to-Weight at Take-off	0.38

Table 17 Tu-144 D Design Synthesis Parameters

Design Parameter	Input Value
Number of Crew	9
Number of Passengers	150
Engine Thrust-to-Weight	5.4
Engine Weight (kg)	3964.2
Engine Volume (m^3)	56
Fuel Density (kg/m^3)	74.63
Weight per Passenger (kg)	170
Volume per Passenger (m^3)	2
L/D ratio, max	7
Average Cruise Specific Impulse (sec)	3650
Cruise Speed	Mach 2
Flight Range (km)	7,250
Cruise Altitude (km)	18.2
Max. Lift Coefficient	0.7
Thrust-to-Weight at Take-off	0.38

Table 18 Concorde Verification Results

Design Parameter	Actual Value	Calculated Value	Percent Error
Take-Off Gross Weight	185,000 kg	183,966 kg	0.559%
Operating Weight Empty	78,700 kg	80,547 kg	2.347%
Planform Area	358.25 m^2	357.317 m^2	0.2604%
Fuel Fraction	0.517	0.517	0.00%
Number of Engines	4	4	0.00%

Table 19 Tu-144 D Verification Results

Design Parameter	Actual Value	Calculated Value	Percent Error
Take-Off Gross Weight	207,000 kg	214,580 kg	3.662%
Operating Weight Empty	99,200 kg	99,195 kg	0.00504%
Planform Area	506.35 m^2	516.297 m^2	1.965%
Fuel Fraction	0.517	0.517	0.00%
Number of Engines	4	4	0.00%

As seen in the above verification results for the Concorde and Tu-144 D successful sizing of the supersonic aircraft has been achieved in re-creating the Concorde and Tu-144 D represented by the low percent errors.

G. Results – Parametric Sizing

The following solution spaces have been generated for the various trade studies being conducted considering different variants of the Fenix Program. Seen below is a visual of the trades being conducted in the Synthesis Parametric Sizing.

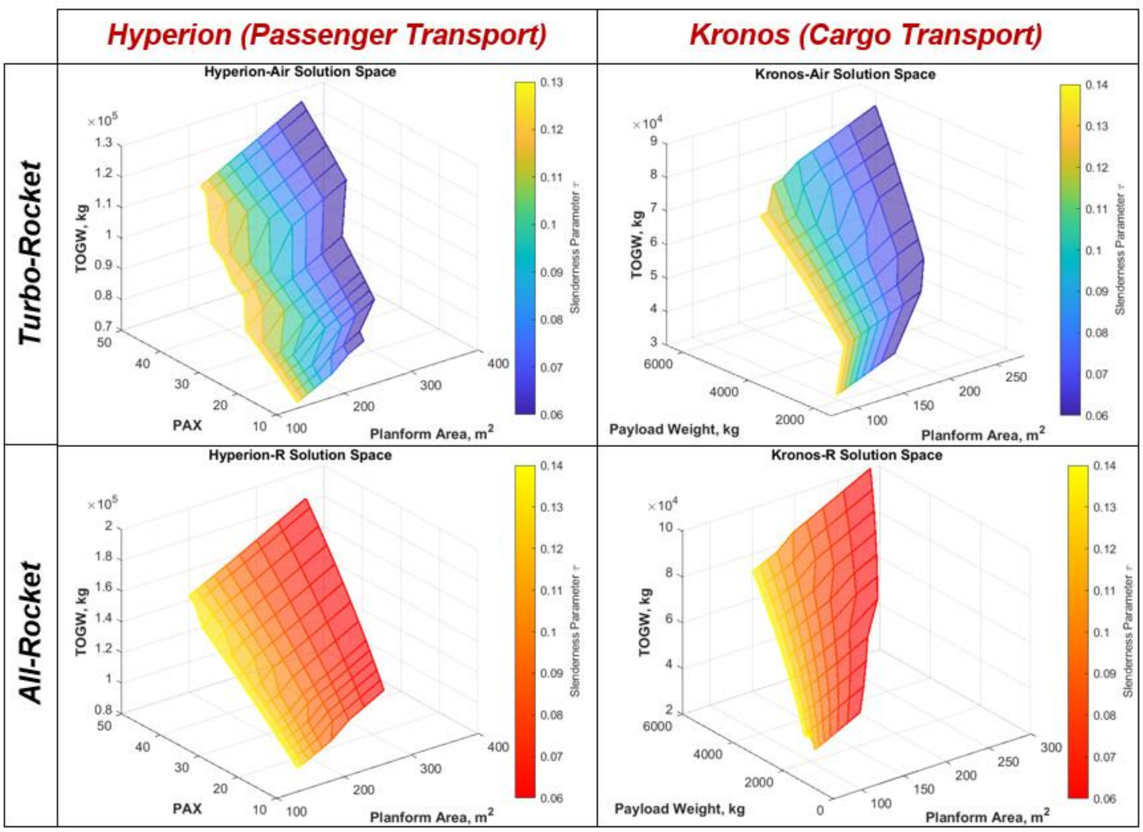


Fig. 66 Fenix Program Trade Solution Spaces from PS

As seen in the solution spaces there are two main vehicles, the Hyperion and the Kronos which correspond to a passenger and cargo variant respectively. The 2nd phase of conceptual design being Configuration Layout has failed many of the design points in all solution space while some remain for use in the 3rd phase, Configuration Evaluation. Seen below is a solution space with the passengers varied in number.

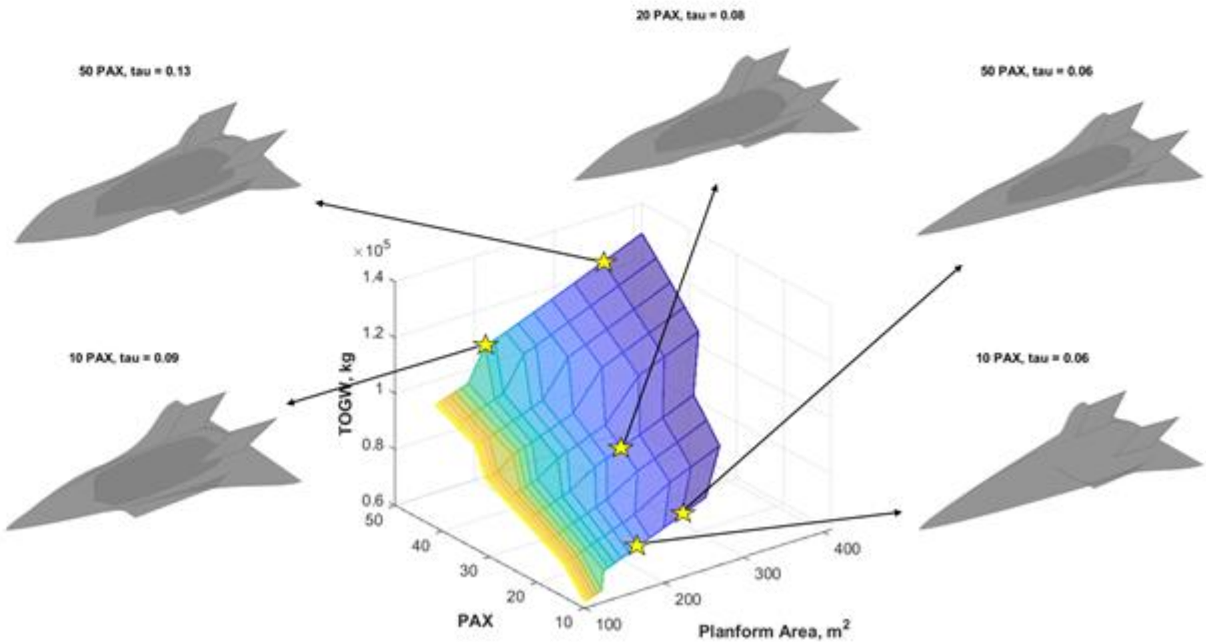


Fig. 67 PS Solution Space Passenger Sizing

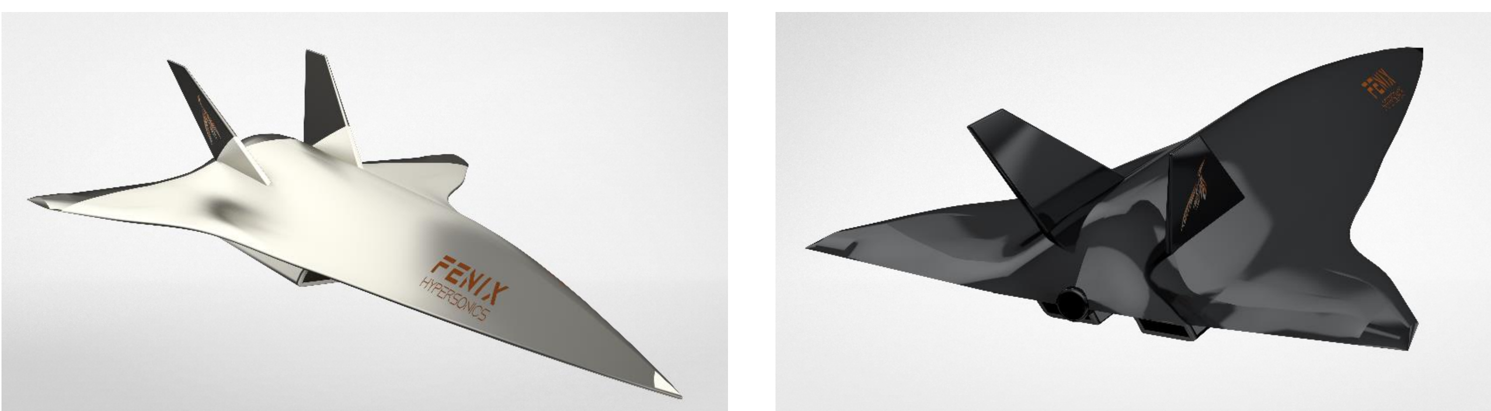


Fig. 68 3D Rendering of Hyperion (left) and Kronos (right)

1. *Trade Matrix In-depth*

The propulsion systems for the airbreathing and rocket configuration were iterated through a series of different engines; these candidates are provided by the propulsion discipline; along with the engine selection, the passenger count is iterated for each Parametric Sizing Design point. Two specific rocket engines served our purposes for various configurations; SpaceX's Merlin 1D rocket engine and Rocket Lab's Rutherford rocket engine both used RP-1/LOX liquid propellant with an oxidizer-to-fuel ratio of 2.7. Being rockets, they need to be throttable to ease the G-forces for the passengers/cargo, the 1st can be throttled 40, 70, and 100% while the Rutherford is quite small thus can have some turned off/on to adjust the thrust vectoring. Seen below are the specifications of each rocket engine:

Table 20 Rocket Selection Specs.

Design Parameter	Rutherford	Merlin 1D
Sea-Level Thrust	24.9 kN	854 kN
Engine Thrust-to-Weight	72.8	184
Engine Volume per Thrust	0.00197 m^3/kN	0.00761 m^3/kN
Engine Weight	35 kg	470 kg
Engine Volume	0.049 m^3	6.5 m^3
Specific Impulse (sea-level)	311 s	282 s
Nozzle Diameter	0.025 m	0.92 m

Despite the Merlin engine having a significantly higher thrust than the Rutherford, only requiring 1 or 2 for a configuration, the Rutherford engine produced lighter vehicles than the Merlin configuration. But the lightest required 12 Rutherfords and the heaviest a whole 31! The Rutherford resulted in a fuel fraction of 0.765 while the Merlin a fuel fraction of 0.81; representing the lower Isp of the Merlin compared to the Rutherford. Despite the Merlin producing heavier vehicles the high number of Rutherfords required did not justify the 'weight savings' of the smaller engines which said 'weight savings' would be offset with increased complexity and support structure for so many engines; thus the all-rocket configuration uses only the Merlin 1D rocket engine.

Similarly, a set of candidates was iterated for the non-combined airbreathing configuration as seen below:

Table 21 Turbo-Jet Non-Combined Cycle Selections

Design Parameter	Olympus 593	J58	GE-YJ93	GE-4
Sea-Level Thrust (wet)	169.52 kN	138.53 kN	135.38 kN	281 kN
Engine Thrust-to-Weight	5.4	5.23	6	6.02
Engine Volume per Thrust	0.04814 m^3/kN	0.06937 m^3/kN	0.08738m^3/kN	0.0757 m^3/kN
Engine Weight	3200 kg	2700 kg	2300 kg	5100 kg
Engine Volume	8.16 m^3	9.61 m^3	11.83 m^3	21.27 m^3
Thrust Specific Fuel Consumption	33.8 g/kN-s	54 g/kN-s	51 g/kN-s	55 g/kN-s
Engine Diameter	1.2 m	1.3 m	1.3 m	1.8 m

Various test solution spaces were generated using each engine, where a sweet spot was seen for each engine for maximum passengers and minimum weight. The GE-4 yielded far greater design point weights than the other engines and was thus removed from the sizing process, similarly, in iterating in a way the sizing process would select the most optimal engine for a design point the J-58 was never selected and was thus also removed from the sizing process.

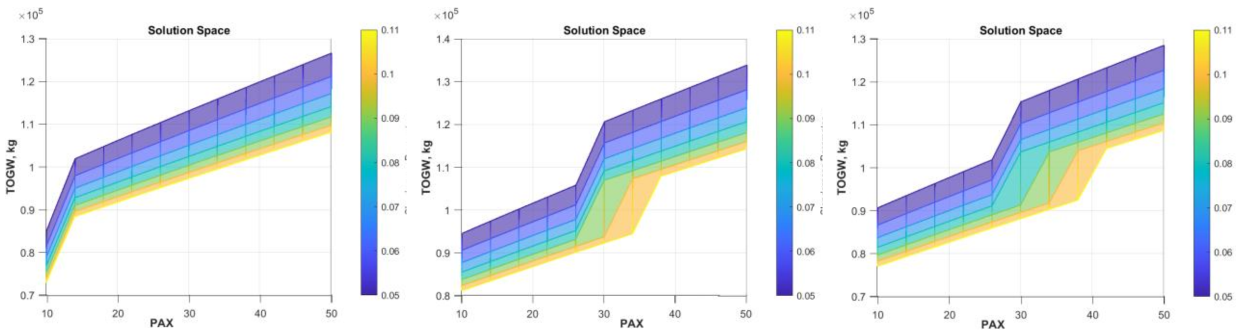


Fig. 69 Olympus Solution-Space (left), J58 Solution-Space (middle), and GE-YJ93 Solution-Space (right) [48]

In removing two engine candidates the Olympus and GE-YJ93 were left for the airbreathing configurations, often the two would be slightly better than the other depending on the size of the craft. The following table outlines the finalized trades for engines in the all-rocket and airbreathing configurations.

Table 22 Final Propulsion System Trades

Design Parameters	All-Rocket	Non-Combined Turbo-Rocket (Merlin 1D for Rocket)	
	Merlin 1D	Olympus 593	GE-YJ93
Engine Thrust-to-Weight	184	5.4	6
Engine Weight	470 kg	3,200 kg	2,300 kg
Engine Volume	6.5 m^3	4.66 m^3	8.33 m^3
Fuel Density	813 kg/m^3	804 kg/m^3	804 kg/m^3
Specific Impulse	282 s	-	-
Fuel Consumption	-	33.8 kg/N-s	51 kg/N-s

In addition to doing a trade study of the engines a payload trade study was executed as well between a passenger and cargo variant. In the case of the passenger variant the number of passengers was incremented from 10 to 50 in units of 4 for cabin layout purposes, in all cases there were 3 crew members. In the cargo variant it is assumed to be unmanned, thus drastically reducing the weight in not requiring passenger systems and more lax requirements on environmental control systems, said cargo payload is iterated from 1000 to 6000 kg in 500 kg units, additionally, the cargo transport can be more slender and aerodynamically optimized due to no 'cabin comfort requirements' thus reducing the drag.

Table 23 Payload Trade Matrix [48]

Design Parameter	Passenger	Cargo
Lower Limit Weight	10 PAX = 1,233 kg	1500 kg
Upper Limit Weight	50 PAX = 6,168 kg	10500 kg
Equivalent Payload Density	52.7 kg/m^3	48 kg/m^3
Total Crew Weight	1,770 kg	0 kg

2. Hyperion-R: All-Rocket Passenger Transport

The following outlines the produced solution space and rendering of Hyperion-R the all-rocket passenger variant for the Fenix program. However, the solution space is not economically or environmentally friendly noting a high weight ratio (due to the oxidizer portion of the rocket) with a huge amount of propellent required per mission. Also seen is a constant fuel fraction of 0.765.

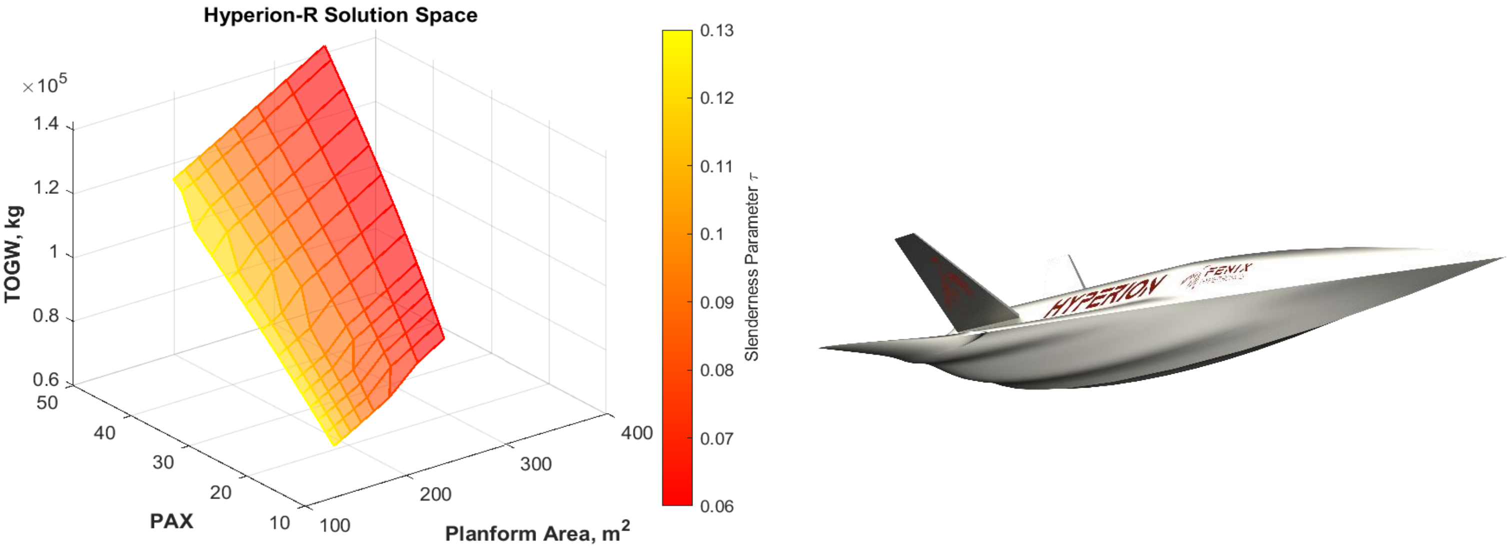


Fig. 70 All-Rocket Passenger Transport Solution-Space (left), Final Hyperion-R Rendering (right)[4]

3. Hyperion-Air: Non-Combined Turbo-Jet Passenger Transport

In sizing the airbreathing passenger transport large jumps in the take-off-gross-weight (TOGW) were observed, this is due to the sizing method switching between the two turbo-jet candidates initially starting with the Olympus engine shortly thereafter switching to the GE-YJ93 and finally back to the Olympus at approximately 107,000 kg for the TOGW.

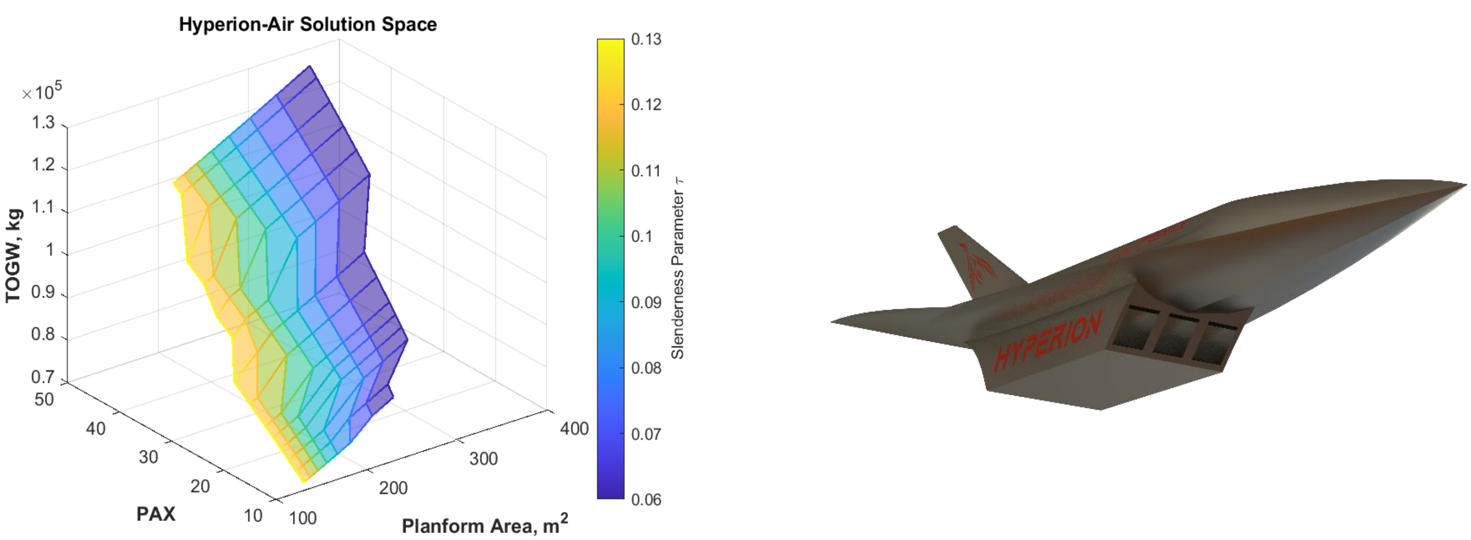


Fig. 71 Hyperion-Air Solution-Space (left), Final Hyperion-Air Rendering (right) [4]

4. Kronos-R: All-Rocket Cargo Transport

Due to not having to carry passengers or a crew the TOGW was significantly reduced for the cargo-transport variant which produced significantly smaller vehicles than the Hyperion solution-space variants.

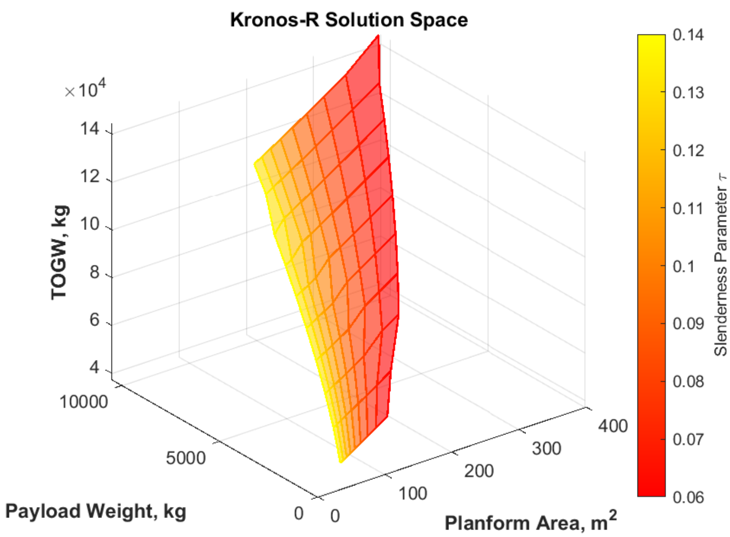


Fig. 72 Kronos-R Solution-Space (left), Final Kronos-R Rendering (right)

5. Kronos-Air: Non-Combined Turbo-Jet Cargo Transport

There are near identical ridges as the passenger variant, Hyperion-Air, showing an identical trading between different air breathing turbo-jets, however the TOGW of Kronos-Air designs were almost the same as the Kronos-R variant alluding to little to no improvement in performance of the airbreather over the rocket variant unlike in the passenger variant, Hyperion.

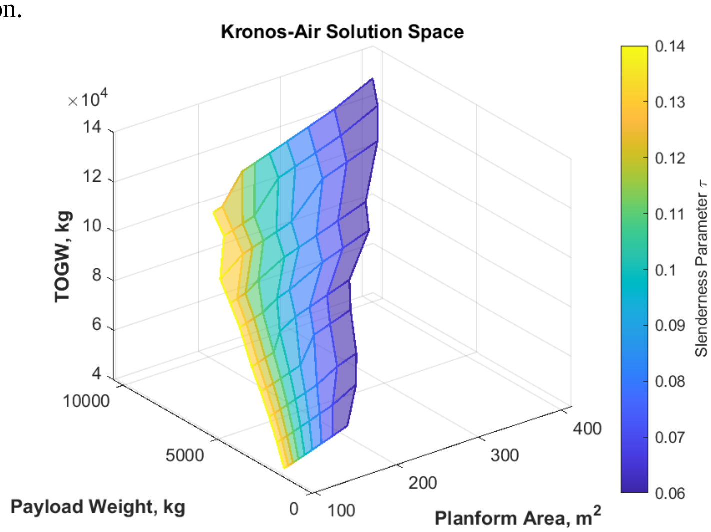


Fig. 73 Kronos-Air Solution-Space

6. Key Takeaway:

Through all the design variants, a lower value of τ (Tau) yielded an increase in the planform area (thus a higher TOGW), however with the higher values of τ the aerodynamic qualities of the design degrade as such a balance must be found to determine the optimal design. This is achieved by iterating the various inputs refining them along the way to achieve the best overall design point.

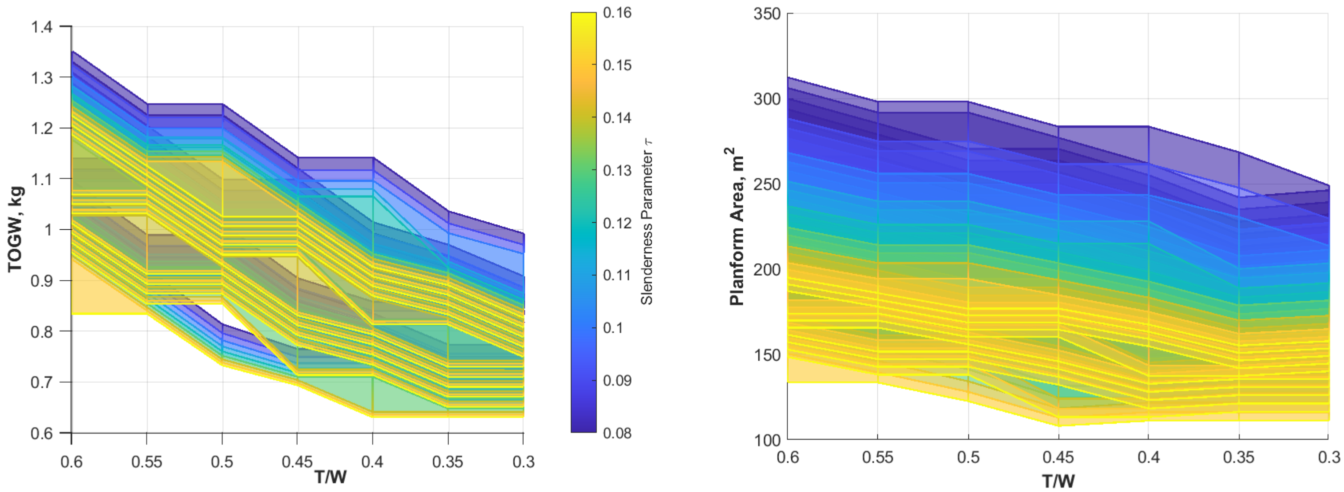


Fig. 74 Thrust-to-Weight Effects on Sizing [48]

Seen in the figures above the T/W has a greater influence over the TOGW than the planform area. The T/W was selected based on semi-empirical analyses of similar aircraft and then iterated from 0.3 to 0.6 for each PAX iteration; this parameter sizing the propulsion system for take-off. The value of 0.4 T/W has the largest range of designs for TOGW for all PAX iterations; to ensure the vehicle can take-off the T/W was kept at 0.4 as it was the most plentiful design both analytically and empirically.

H. Results - Configuration Layout

The Geometry discipline was the main power-house for the CL phase of combat. Their methods fully-defined each vehicle design points geometry and modeled each vehicle by parametrizing each design point. The wing is a feat of engineering being area-ruled by taking cross-sections the wing and plotting each against the Sears-Haack body to achieve a theoretical minimum wave drag, an essential quality for the Fenix program.

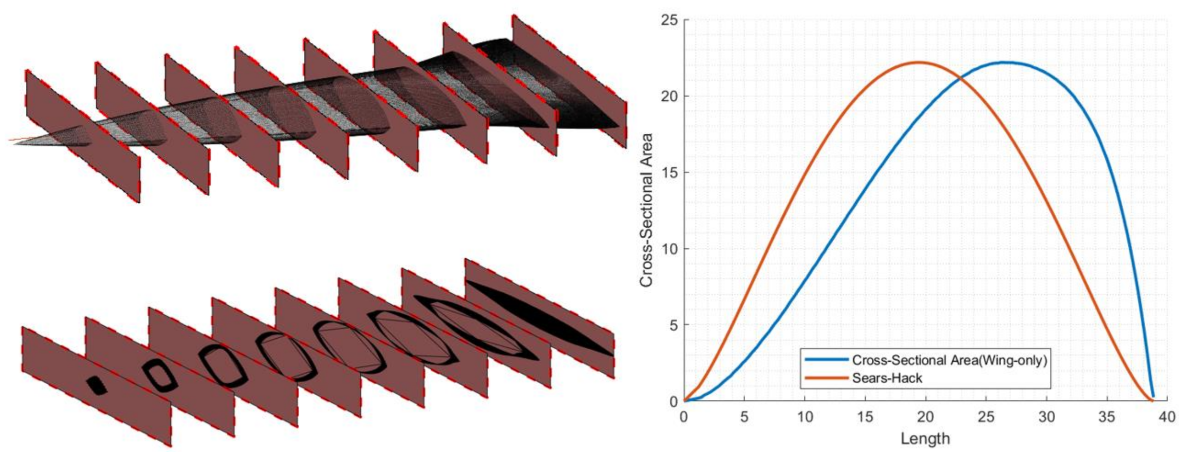


Fig. 75 Cross-Sectional Cuts used to Area-Rule

In processing the data from the Parametric Sizing a maximum τ of 0.13 was found for all configurations where any greater slenderness ratio the craft could not take-off properly due to not enough planform area.

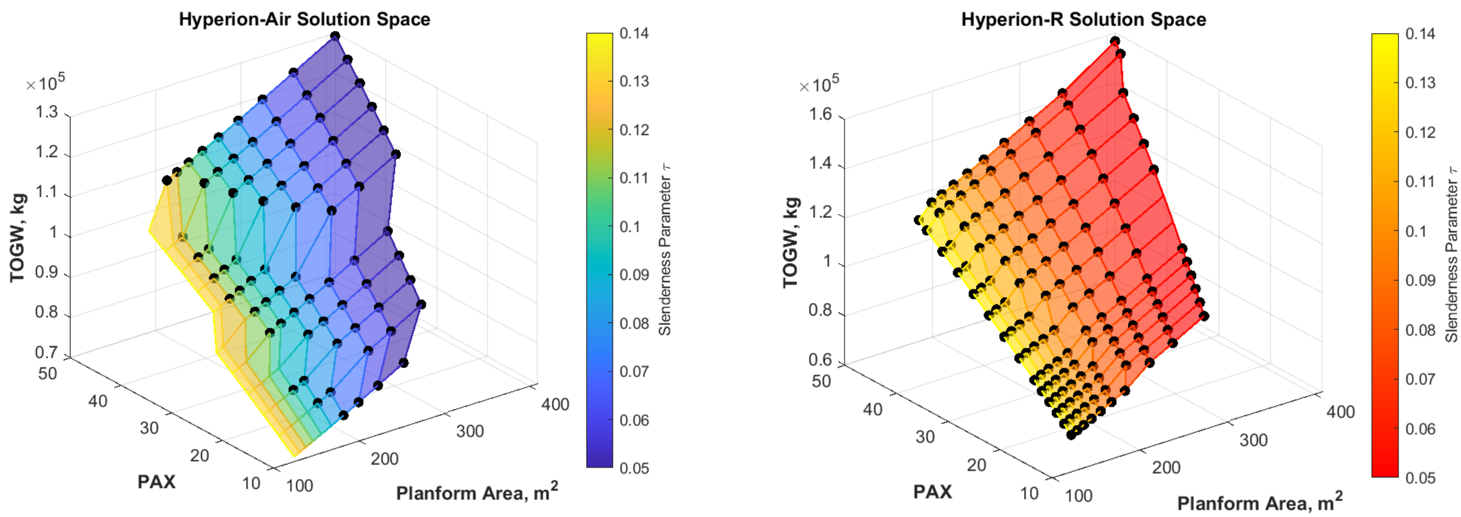


Fig. 76 Configuration Layout Solution-Spaces

Each black point in the above figures represent design points that passed Configuration Layout, set to go on to the final phase of the conceptual design process, Configuration Evaluation. It is seen there is a drop of passing designs after a τ value of 0.09 for the airbreathing variants, however the all-rocket variants have a significantly larger range of technical feasibility.

I. Results – Configuration Evaluation

Finally, the Configuration Evaluation analyzed the remaining vehicles crossing between many different disciplines between each phase. The Marketing lead (the author) found the passenger transport to have a viable business-case, significantly stronger than the cargo transport variant in generating more revenue. In a Cost discipline analysis, it was found that a greater passenger number and τ correlated to higher ticket prices and thus ROI, however there is a limit due to waning demand with greater premiums paid this was balanced to dictated the final optimal designs.

Table 24 Optimal Design Configuration for Hyperion-Air (left) and Hyperion-R (right)

Design Parameter	Value
Slenderness	0.11
Passengers	36
Planform Area	205.9 m^2
Take-off Gross Weight	91,788.3 kg
Operating Empty Weight	29,597.6 kg
Payload Weight	4,441.1 kg
Fuel Fraction	0.6245
Number of Turbojets	3
Number of Rockets	1
Length	25.9 m
Span	16.71 m
Fore Sweep	75°
Aft Sweep	55°

Design Parameter	Value
Slenderness	0.09
Passengers	44
Planform Area	247.76 m^2
Take-off Gross Weight	120,065.9 kg
Operating Empty Weight	22,367.5 kg
Payload Weight	5428 kg
Fuel Fraction	0.765
Number of Rockets	2
Length	32.05 m
Span	16.67 m
Fore Sweep	78°
Aft Sweep	65°

VI. ABET Outlines

A. Outcome 2: Design System or Process to Meet Needs

The main task for the author lay within organizing the Weights & Balances (W&B) and Synthesis disciplines; the latter of which is concerned with formulating and executing how each discipline works together at each phase of the conceptual design in PS-CL-CE to design a successful system to generate and characterize a vehicle capable of serving as a Hypersonic commercial aircraft.

In the W&B discipline the author designed processes to determine the CG and inertias of a characterized vehicle as well as approximate the weight of several components of said vehicle; these built-up systems are represented in the form of IDAs as seen in the Weights & Balances section of this report and executed in the form of MATLAB functions.

As far as the Synthesis discipline goes, the author aided in the design of the Parametric sizing process which is dominated by the Synthesis discipline with unchanging inputs (due to iteration) from other disciplines. Similarly, the Configuration Layout and Configuration Evaluation processes were designed primarily by the Chief engineer and the author. Each of the systems designed (PS-CL-CE) are represented as MDA1, MDA2, and MDA3 respectively.

B. Outcome 3: Ability to Function on Multidisciplinary Teams

The author acted as the Chief Engineer in the 1st semester of Senior Design with the main task to guide the team in encouraging disciplines to work cohesively in a multi-disciplinary way. In other words, to ensure each discipline considers other disciplines and no one discipline was controlling the design process. This is demonstrated in further detail in the methodology section. In both semesters of Senior Design under Dr. Chudoba each member has been involved in two separate disciplines to help each member cultivate the interplay between different disciplines to understand no discipline can be considered alone. This is especially useful in visualizing how aircraft and design in general cannot effectively optimize a design by optimizing a single discipline, but by considering and balancing out each discipline with each other an effective optimized design may be realized. Thus, engraining the understanding importance of multi-disciplinary teams.

Expectation timelines were semi-useful in expediting the projects and keep members accountable to their tasks, this depended heavily on the Chief's and discipline leads ability to enforce and remind members of their timelines and tasks. An effective way to ensure performance in the event a discipline or member was not participating or having constant time-delays was used in first threatening to report the discipline/member to the graduate assistant with a grace period, fortunately, under-performing disciplines/members have been able to complete tasks within said grace period. This method aided in training the ability of the members to understand their place in a team.

C. Outcome 4: Understand Professional and Ethical Responsibility

To provide a safe design for the consumer is the utmost ethical responsibility for an aerospace engineer; primarily the Stability & Control and Structures disciplines have the greatest influence on the safety of a design while the Certifications discipline enables the safety of a design to be evaluated within reasonable parameters. Each of these disciplines are part of the process to detect dangers, discomforts, and possible scenarios caused by the trajectory, aerothermal loads (a major issue in Hypersonic design), or simply the unexpected such as a one-engine-out situation. It is vital these disciplines achieve an in-depth and accurate analysis while reporting their findings honestly without fear of repercussions.

All too often, corporate greed will push the managerial side of things to prefer to "fudge the numbers" to bring about a more cost-effective design at the expense of safety or double checking everything; this fault lies with the business as a whole and the engineers involved (if they purposely didn't report their concerns or qualms about a project). The professional environment is aligned where reporting failures in results is not to be punished but learned from, this has been reflected in this CAPSTONE project in how each weekly report builds upon itself and a failure to meet the mission objectives is not indicative of a lack of effort on the team; this was the case in the first project where the mission objectives were not met by either of the competing teams.

Additionally, this CAPSTONE project has stressed the importance of learning what has already been done and achieved rather than attempting to 'reinvent the wheel' where 'literature review' has focused on developing an understanding of methodologies, history, and a scope of the project (and in referencing sources) leading to a great deal of transparency for others to build off what has been achieved. This thought process is not codified to engineering alone but to approaching any topic of interest from business ventures, to writing books or even learning how to surf, this can be considered a method of how to properly study, document, and organize results for later use.

D. Outcome 5: Ability to Communicate Effectively

The presentations given in this CAPSTONE set of courses focused on tailoring what is being presented to the core points in the results and methods being understandable by the common man while also providing ample detail for the specialist. As the saying goes "The details are in the reports." – Dr. Chudoba, this holds so very true where this report is designed to communicate the results, methods, and work done in an organized manner with everything documented.

In the reports and presentations figures, pictures, tables, and all other manner of visuals were used to ease the understanding of what was being presented as pure walls of text are convoluted and boring to put it simply. The use of IDAs and MDAs to represent the flow of information and lay out planned methodologies are a great example of this in how an extremely complex set of ideas may be conveyed in a single image; the author plans to extend this method of presenting and planning in the future no matter the subject.

E. Outcome 7: Understand Impact of Engineering Solutions

The CAPSTONE program has pushed the understanding of why engineering is needed and performed in the bigger picture in how business cases are created around providing a solution to a problem and addressing a global market need/demand whether it be for commercial/private purposes or to support the United States military industrial complex. This is especially important in the main subject of focus this past year concerning Hypersonics in how both Russia and China, the United States' primary global rivals, are ahead of the United States by many bounds putting the nation at risk in threatening American sovereignty and powerbase in both the international and domestic realms of influence.

In completing a market analysis for the commercial aircraft focus the author has developed a numerical method of analyzing the demand for a product and the limitations of such designs to remain profitable if developed; this is vital for any business venture in assessing the risks and ROI of a project before investing immense resources and manpower.

F. Outcome 8: Recognize the Need and Ability to Engage in Lifelong Learning

A major outcome of the CAPSTONE program was the teaching and push of learning throughout and educated oneself, this was seen in literature review and research being continued at every point in the project from day one to the final presentation. Representee of industry, those who do not continue to 'yearn to learn' fall behind others.

Hypersonic vehicle design is not formally taught neither is vehicle design or project management in the official Aerospace Engineering degree planning, this project has led those involved to expand their knowledge base by leaps and bounds to fulfill deliverables adequately. No matter the focus of the project the case would have been the same such as if there were a focus on rotorcraft, nautical-craft, or space vehicle design. An engineer is assessed by not only what knowledge they bring to the table initially but their ability to become rapidly educated and competent with subjects a project calls for. As a result, this project has really shown that college is by no means the end of 'learning' but simply the beginning, for in college ones educated is guided along but in industry and all of life one must lead themselves in the pursuit of knowledge and wisdom.

VII. Conclusion

High-speed air-travel in the supersonic and hypersonic speed regimes has been found to have a wide variety of business-cases all with the potential for massive profits; attempted in the past, but only now do we have the technological ability to usher in a new age of supersonic travel. The Fenix program addressed this desire to reach to the future and design a vehicle capable of profitably achieving similar mission requirements as the age-old Saenger II, a dream of the past.

Pursuing the conceptual design process in a multidisciplinary perspective, the Fenix team engaged in 9 disciplines of topics, culminating in Parametric Sizing, Configuration Layout, and Configuration Evaluation: starting with thousands of designs, to hundreds, and finally the optimal designs. Each design was run through a variety of trad matrixes to no just find the best for a single discipline but the best configuration for all the disciplines as any project in life should be approached, not from one man's perspective but from many so that nothing is left unseen. Two optimal designs were found one for a non-combined cycle airbreathing-rocket variant and an all-rocket variant both being passenger transport configurations, 36 PAX, 0.11 Tau and 44 PAX, 0.09 Tau respectively, as the cargo configurations were determined to not have a strong enough business-case to pursue for a venture in the nascent market of supersonic air-travel.

Appendix A: History of Program Development

A. Week 1

The first week consisted of organizing the team structure and understanding the deliverables for the team.

B. Week 2

Literature search began, doling out tasks to other Weights and Balances members, verification aircraft and method buildup. Setup of Monday.com, LucidCharts, Zotero, and MS Teams.

C. Week 3

Begin code using HASA and FLOPS Weight Module, HASA has been fully coded, FLOPS is in progress. Synthesis aid in brainstorming constraints and initial weight coefficient estimations.

D. Week 4

Requested FLOPS 9.0.0 software from NASA distribution center. More literature search into aircraft historical buildup of knowledge.

E. Week 5

Rebuilt FLOPS legacy software to modern FORTRAN syntax, able to use for verification in determining estimated weight breakdowns of vehicles, the 1st attempted was a supersonic transport, then Concorde, the Tu-144 will be assessed next to establish verification. Discussion about lack of manpower in the Geometry discipline due to the Structures discipline being treated as a separate disciplines; overlap with Geometry and W&B but not enough to warrant 'integration'. Once verification via FLOPS and preliminary weight estimation code is complete (about 70% done) more focus on Synthesis discipline.

F. Week 6

FLOPS now fully usable, recreated the Concorde for a detailed weight breakdown seen in part F of the W&B section and in Appendix C: Section B. Tu-144 in progress due to lacking some information regarding literature the aircraft capabilities and mission requirements, will be complete come Week 7. Weight Estimation code complete as seen in Appendix C; waiting on inputs from various disciplines to test code, due to its reliance on HASA and FLOPS semi-empirical analyses should be accurate. Going forward, documenting the W&B methodology used in the code for weight estimation is needed as well as documenting the Tu-144 and Concorde data buildup which has been neglected in this report thus far. A mini module for the Synthesis discipline will be created for the W&B to be involved with ensuring accuracy on the weight side of things in the PS phase of conceptual design, this will be the layaway for the author to get re-involved with the Synthesis discipline. Lastly, the CG determination code will be started once a layout has been provided from the geometry discipline, which has already been sent a list of what W&B wants from them. Similarly, the entirety of the W&B code will be designed with parent codes so everything can be run as a function for ease of use by non-W&B educated users. With the complete method verification, documenting the method in the works (will be finished by mid-term presentation), and trade study capable code the W&B discipline will be in good shape for the mid-term presentation. It has been seen much of the back-end work has fallen to the author and the front-end work to Ariel regarding the W&B discipline.

G. Week 7

The Concorde and Tupolev Tu-144 LL have been re-created in FLOPS for verification, this was compared to the W&B weight component estimation code with an error of 1.83 % for the Concorde's total weight, incredibly close, showing an accurate method used for W&B. Still waiting on Propulsion and Jeff for a cycle deck for various engines to fully unlock the usability of FLOPS. Some issues have come up in recreating the Tu-144 LL in the W&B weight component code in that data on the engine airflow rate and the fuel distribution between the wings and fuselage are lacking but necessary to produce results.

H. Week 8

Method IDA for weight estimation code created for midterm presentation, new FLOPS verification for Tu-144 LL, W&B component code for Tu-144 LL (based on estimations for missing parameters). New IDAs, catalog of verification data, design of CG and Inertia code but waiting on Geometry to provide an initial layout before executing design.

I. Week 10

Verification W&B and FLOPS for the Gulf Stream 550 business jet, preliminary marketing research, document data on Concorde, tu-144LL and Gulfstream 550. Also, CG & inertias code build to finish CL phase for W&B. Further verification for Synthesis for the Concorde and Tu-144.

J. Week 11

CL W&B code completed, Synthesis CL total code build nearly done with help from Noah, however, the Trajectory discipline is causing delays in the process. Completed CG shift range code (depending on point in mission profile). Helped Geometry sort out some of their point cloud indexes due to inconsistences in models being generated (half the model had more points than the other half). Marking research will be documented next week as well as the Gulf Stream 550 business jet (delays due to incorrect initial parameters). Plan for upcoming week: CE code finish for W&B, team code builds for CE begin, start drafting final presentation (mainly marketing and W&B portion for author), finishing placing components of designs.

K. Week 12-13

CL code completed, various issues propped up requiring rewrites by the author of the Synthesis, Geometry, and WB codes to function properly. Author set the internal layout of the vehicle; it won’t shift much across designs with only minor differences. Helped trouble shoot Cost codes due to broken paths and inconsistent automation. CE is ongoing with delays due to lack of push from Chief Engineer which is concerning given the Final Presentation is in 4 days from the authoring of this section. Further verification for WB completed including the G 550, Falcon 900, and Learjet 45. Preliminary analysis by the author revealed the craft to have a selling cost in the $400 million dollar range (includes a 30% mark-up cost for profit).

L. Week 13-16

CE phase done manually, rework of multiple codes for W&B and Synthesis, documentation of Marketing, W&B results, Synthesis, final results, final renderings. Prep work for final presentation and graphics, complete final presentation. Selected final design for the Fenix program for rocket-based and airbreathing-based.

Appendix B: Aircraft Synthesis Methods

An appendix of systems used for synthesis complied by various researchers in the field.

Table 25: Systems and Methods for Aircraft Synthesis [32]

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

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

FPDB & AS	Future Projects Data Banks & Application Systems	Airbus Industrie	Transonic Transport Aircraft	1995
FPDS	Future Projects Design System	Hawker Siddeley Aviation Ltd	Aircraft	1970
FRICTION	Skin friction and form drag code			1990
FVE	Flugzeug VorEntwurf	Stemme GmbH & Co. KG	GA Aircraft	1996
GASP	General Aviation Synthesis Program	NASA Ames Research Center	GA Aircraft	1978
GPAD	Graphics Program For Aircraft Design	Lockheed-Georgia Company	Aircraft	1975
HACDM	Hypersonic Aircraft Conceptual Design Methodology	Turin Polytechnic	Hypersonic aircraft	1994
HADO	Hypersonic Aircraft Design Optimization	Astrox	?	1987-
HASA	Hypersonic Aerospace Sizing Analysis	NASA Lewis Research Center	AeroSpace Vehicle	1985, 1990
HAVDAC	Hypersonic Astrox Vehicle Design and Analysis Code	Astrox		1987-
HCDV	Hypersonic Conceptual Vehicle Design	NASA Ames Research Center	Hypersonic Vehicles	
HESCOMP	HElicopter Sizing and Performance COMputer Program	Boeing Vertol Company	Helicopter	1973
HiSAIR/Pathfinder	High Speed Airframe Integration Research	Lockheed Engineering and Sciences Co.	Supersonic Commercial Transport Aircraft	1992
Holist	?	?	Hypersonic Vehicles with Airbreathing Propulsion	1992
ICAD	Interactive Computerized Aircraft Design	USAF-ASD	?	1974
ICADS	Interactive Computerized Aircraft Design System	Delft University of Technology	Aircraft	1996
IDAS	Integrated Design and Analysis System	Rockwell International Corporation	Fighter Aircraft	1986
IDEAS	Integrated DEsign Analysis System	Grumman Aerospace Corporation	Aircraft	1967
IKADE	Intelligent Knowledge Assisted Design Environment	Cranfield University	Aircraft	1992
IMAGE	Intelligent Multi-Disciplinary Aircraft Generation Environment	Georgia Tech	Supersonic Commercial Transport Aircraft	1998
IPAD	Integrated Programs for Aerospace-Vehicle Design	NASA Langley Research Center	AeroSpace Vehicle	1972-1980
IPPD	Integrated Product and Process Design	Georgia Tech	Aircraft, weapon system	1995
JET-UAV CONCEPTUAL DEISGN CODE		Northwestern Polytechnical University, China	Medium range JET-UAV	2000
LAGRANGE			Optimization	1993
LIDRAG	Span efficiency			1990
LOVELL				1970-1900
MAVRIS	an analysis-based environment	Georgia Institue of Technology		2000
MELLER		Daimler-Benz Aerospace Airbus	Civil aviation industry	1998
MacAirplane	(-)	Notre Dame University	Aircraft	1987
MIDAS	Multi-Disciplinary Integrated Design Analysis & Sizing	DaimlerChrysler Military	Aircraft	1996
MIDAS	Multi-Disciplinary Integration of Deutsche Airbus Specialists	DaimlerChrysler Aerospace Airbus	Supersonic Commercial Transport Aircraft	1996
MVA	Multi-Variate Analysis	RAE (BAC)	Aircraft	1991
MVO	MultiVariate Optimisation	RAE Farnborough	Aircraft	1973

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

TIES	Technology Identification, Evaluation, and Selection	Georgia Institute of Technology		1998
TRANSYN	TRANsport SYNthesis	NASA Ames Research Center	Transonic Transport Aircraft	1963-(25years)
TRANSYS	TRANsportation SYStem	DLR (Aerospace Research)	AeroSpace Vehicle	1986-
TsAGI	Dialog System for Preliminary Design	TsAGI	Transonic Transport Aircraft	1975
VASCOMPII	V/STOL Aircraft Sizing and Performance Computer Program	Boeing Vertol CO.	V/STOL aircraft	1980
VDEP	Vehicle Design Evaluation Program	NASA Langley Research Center	Transonic Transport Aircraft	
VDI				
Vehicles	(-)	Aerospace Corporation	Space Systems	1988
VizCraft	(-)	Virginia Tech	Supersonic Commercial Transport Aircraft	1999
Voit-Nitschmann				
WIPAR	Waverider Interactive Parameter Adjustment Routine	DLR Braunschweig	AeroSpace Vehicle (Waverider)	
X-Pert	(-)	Delft University of Technology	Aircraft	Paper 1992

Appendix C: Aircraft Database

A.Concorde Aircraft Data

Table 26 Concorde Aircraft Data

Aircraft Data (External)	Symbol	Value	Unit	Aircraft Data (Internal)	Symbol	Value	Unit
Planform Area	Sref	3856	ft^2	Wing span	B	83.83333333	ft
Takeoff Gross Weight	TOGW	389000	lbs.	baggage weight	BPP	44	lbs.
Operating Empty Weight	OEW	172000	lbs.	carrier based ac switch	CARBAS	1	
Wetted Area	Swet	7793.2126	ft^2	cargo carried in fuse (not bags)	CARGOF	0	lbs.
Length	L	202.5	ft	cargo carried in wing (not bags)	CARGOW	0	lbs.
Wing Span	b	83.833333	ft	atmospheric pressure ratio	DELTA	0.071379967	
Taper Ratio*	λ	0		design range	DESRNG	3915	nmi
Ahorizstab/Awing	Ahfp	0		max fuse depth	DF	10.8333	ft
Avertstab/Awing	Avfp	0.0946577		design gross weight	DG	389000	
horiz stab planform area	Swfh	0	ft^2	max fuel capacity	FMXTOT	211797	lbs.
vert stab planform area	Swfv	365	ft^2	avg diam of eng	FNAC	3.975	
Aspect Ratio	AR	1.7		#fuse eng	FNEF	0	
wing thickness to chord ratio*	t/c	0.03		tot # eng	FNENG	4	
1/2 Swet	Stb	3896.6063	ft^2	# wing eng	FNEW	4	
Total Momentum Thrust *	Ttot	124000	lbf	fuse planform area	FPAREA	34.82229218	

Max Dynamic Pressure*	Qmax	2771236.3	psf
Ultimate Load Factor*	ULF	1.6041237	
Modifying Factor*	mf	1.12	
Engine Airflow* (mass flow rate)	Wa	410	lbs./s
# of Engines	Neng	4	
Thermal Protec. Weight*	Wins	0.0171677	lbs./ft^2
Equivalent Diameter*	Dbe	1343.6179	ft
Vehicle volume *	Vtot	200985408	ft^3
volumetric efficiency	ηvol		
tank density	ρtank		
tank volume	Vtank		
tank weight	Wtank		
Height	h	28.666667	ft
Sub weight values			
body	σ	105837.16	
tail	Λ	0	
hydraulics	Ψ	648.16842	
electrical	θ	2352.7786	
Additional Information			
Olympus 593 Mk 610	ENG	7000	lbs.
fuel capacity	FMXTOT	26286	lbs.
Max T-O Weight	TOGW	389000	lbs.
altitude (max)	Amax	51300	ft
air density	ρair	3.64	slugs/ft^3
max speed	vmax	1233.96	ft/s

thrust of each eng	FTHRST	38050	lbs.
aux fuel tanks	FULAUX	0	
fuel density ratio (not jet)	FULDEN	6.7	lbs./gal
factor for wing fuel cap	FWMAX	23	
hydr sys pressure	HYDPR	3000	psi
number of flight crew	NFLCR	5	
number of fuse	NFUSE	1	
number of galleys	NGALC	0	
number of passengers	NPASS	128	
#buisness pass	NPB	128	
#first class pass	NPF	0	
#tourist class pass	NPT	0	
# flight attendants	NSTU	4.2	
# fuel tanks	NTANK	13	
dive maneuver dyn press	QDIVE	0	psf
tot movable wing SA	SFLAP	344.4	ft^2
wing span	SPAN	130	ft
ref wing area	SW	3856	ft^2
quart chord sweep area	SWEEP		
weighted avg wing t/c	TCA	0.03	
taper ratio of wing	TR	0	
ult load factor	ULF	1.604123711	
wing var sweep factor	VARSWP	0	
max mach number	VMAX	2.04	
max fuse width	WF	9.4167	ft
tot fuse length	XL	204	ft
length of pass compartment	XLP	129	ft
taper ratio of wing	TR	0	
Quarter chord sweep angle	SWEEP	55	deg
Aspect Ratio	AR	1.7	
Max T-O weight	GW	389,000	lbs.
max fuel capacity in wing	FULWMX	145797	lbs.
max fuel cap in fuse	FULFMX	66000	lbs.
max cruise mach	VCMN	2.05	
max mach number	VMMO	2.17	
number of cargo containers	NCON	0	
cabin area	Acabin	69.64458436	ft
weight per passenger	WPPASS	165	lbs.

B. Tu-144 LL Aircraft Data

Table 27 Tu-144 LL Aircraft Data

Aircraft Data (External)	Symbol	Value	Unit
Planform Area	Sref	5450.3	ft^2
Takeoff Gross Weight	TOGW	410,000	lbs.
Operating Empty Weight	OEW	220,460	lbs.
Wetted Area	Swet	11146.16172	ft^2
Length	L	215.5833333	ft
Wing Span	b	94.5	ft
Taper Ratio*	λ	0.122	
Ahorizstab/Awing	Ahfp	0	
Avertstab/Awing	Avfp	0.131699173	
horiz stab planform area	Swfh	0	ft^2
vert stab planform area	Swfv	717.8	ft^2
Aspect Ratio	AR	1.66	
wing thickness to chord ratio*	t/c	0.04	
1/2 Swet	Stb	5573.080859	ft^2
Total Momentum Thrust *	Ttot	216000	lbf
Max Dynamic Pressure*	Qmax	5839888.51	psf
Ultimate Load Factor*	ULF	1.690721649	
Modifying Factor*	mf	0.95	
Engine Airflow* (mass flow rate)	Wa	592.641	lbs./s
# of Engines	Neng	4	
Thermal Protec. Weight*	Wins	1.409831667	lbs./ft^2
Equivalent Diameter*	Dbe	1336.896664	ft
Vehicle volume *	**Vtot**	**211835520**	**ft3**
volumetric efficiency	ηvol	0.7	
tank density	ρtank		
tank volume	Vtank		
tank weight	Wtank	209440	
Height	h	41.16666667	ft
Sub weight values			
body	σ	176784.732	
tail	Λ		
hydraulics	Ψ		
electrical	θ		
Additional Information			
Engine: Kolesov RD-36-51	ENG	8600	lbs.
fuel capacity	FMXTOT	209440	lbs.
Max T-O Weight	TOGW	410,000	lbs.
altitude (max)	Amax	59000	ft
air density	ρair	2.26	slugs/ft^3
max speed	vmax	2273.333	ft/s

Aircraft Data (Internal)	Symbol	Value	Unit
Wing span	B	94.5	ft
baggage weight	BPP	44	lbs.
carrier based ac switch	CARBAS	0	
cargo carried in fuse (not bags)	CARGOF		lbs.
cargo carried in wing (not bags)	CARGOW		lbs.
atmospheric pressure ratio	DELTA	0.07138	
design range	DESRNG	3500	nmi
max fuse depth	DF	11.25	ft
design gross weight	DG	410,000	
max fuel capacity	FMXTOT	209440	lbs.
avg diam of eng	FNAC	4.875	
#fuse eng	FNEF	0	
tot # eng	FNENG	4	
# wing eng	FNEW	4	
fuse planform area	FPAREA	673.92164	
thrust of each eng	FTHRST	55000	lbs.
aux fuel tanks	FULAUX	0	
fuel density ratio (not jet)	FULDEN	1	lbs./gal
factor for wing fuel cap	FWMAX	23	
hydr sys pressure	HYDPR	3000	psi
number of flight crew	NFLCR	3	
number of fuse	NFUSE	1	
number of galleys	NGALC	0	
number of passengers	NPASS	150	
#buisness pass	NPB	0	
#first class pass	NPF	11	
#tourist class pass	NPT	139	
# flight attendants	NSTU	4.75	
# fuel tanks	NTANK	17	
dive maneuver dyn press	QDIVE	0	psf
tot movable wing SA	SFLAP	447	ft^2
wing span	SPAN	94.5	ft
ref wing area	SW	4741.5	ft^2
quart chord sweep area	SWEEP	57	
weighted avg wing t/c	TCA	0.04	
taper ratio of wing	TR	0.122	
ult load factor	ULF	1.6907216	
wing var sweep factor	VARSWP	0	
max mach number	VMAX	2.35	
max fuse width	WF	17.083333	ft
tot fuse length	XL	215.5	ft
length of pass compartment	XLP	196.5	ft

taper ratio of wing	TR	0.122	
quart chord sweep area	SWEEP	57	deg
weighted avg wing t/c	AR	1.66	
Max T-O weight	GW	396830	lbs.
max fuel capacity in wing	FULWMX	192560.04	lbs.
max fuel cap in fuse	FULFMX	209440	lbs.
max cruise mach	VCMN	2.3	
max mach number	VMMO	2.35	
number of cargo containers	NCON	0	
cabin area	Acabin	229.21082	ft
dihedral angle	DIH	-7	deg
aspect ratio of VT	ARVT	1.13	
taper ratio of VT	TRVT	0.233	
weight of baseline engine	WENG	8600	lb
fuel capacity in wing	**FULWMX**	**197660**	**lb**
fuel capacity in fueslage	**FULFMX**	**-39470**	**lb**
max landing approcah velocity	VAPPR	283	mph
max usable fuel weight	FUEMAX	187380	lb
ramp weight	RAMPWT	407850	lb
fixed OP empty weight	DOWE	187400	lb
area of canard	SCAN	179.63	ft^2
ar of canard	ARCAN	1.7	
tr of canard	TRCAN	0.6875	
sweep of VT	SWPVT	47.4	DEG
take off fuel flow	TAKOFF	374785.85	lb/hr/engine
length of main landing gear	XLMLG	60.96	in
max landing length	FLLDG	8432	ft
weight per passenger	WPPASS	165	lbs.

C.Gulfstream G550 Aircraft Data

Table 28 Gulfstream G550 Aircraft Data

Aircraft Data (External)	Symbol	Value	Unit
Planform Area	Sref	1137	ft^2
Takeoff Gross Weight	TOGW	91,000	lbs.
Operating Empty Weight	OEW	48,300	lbs.
Wetted Area	Swet	2319.647968	ft^2
Length	L	96.41666667	ft
Wing Span	b	90.83333333	ft
Taper Ratio*	λ	0.26	
Ahorizstab/Awing	Ahfp	0.215364996	
Avertstab/Awing	Avfp	0.123658751	
horiz stab planform area	Swfh	244.87	ft^2
vert stab planform area	Swfv	140.6	ft^2

Aircraft Data (Internal)	Symbol	Value	Unit
Wing span	B	90.833333	ft
baggage weight	BPP	44	lbs.
carrier based ac switch	CARBAS	0	
cargo carried in fuse (not bags)	CARGOF		lbs.
cargo carried in wing (not bags)	CARGOW		lbs.
atmospheric pressure ratio	DELTA	0.07138	
design range	DESRNG	6750	nmi
max fuse depth	DF	7.83	ft
design gross weight	DG	91,000	
max fuel capacity	FMXTOT	41489	lbs.
avg diam of eng	FNAC	4.875	

Aspect Ratio	AR	7.36	
wing thickness to chord ratio*	t/c	0.1	
1/2 Swet	Stb	1159.823984	ft^2
Total Momentum Thrust *	Ttot	30770	lbf
Max Dynamic Pressure*	Qmax	1289906.883	psf
Ultimate Load Factor*	ULF	4.92	
Modifying Factor*	mf	0.95	
Engine Airflow* (mass flow rate)	Wa	592.641	lbs./s
# of Engines	Neng	2	
Thermal Protec. Weight*	Wins	0	lbs./ft^2
Equivalent Diameter*	Dbe	5.611231043	ft
Vehicle volume *	Vtot	1669	ft3
volumetric efficiency	ηvol	0.7	
tank density	ρtank		
tank volume	Vtank		
tank weight	Wtank	41489	
Height	h	25.83333333	ft
Sub weight values			
body	σ	63159.89252	
tail	Λ	789110718.1	
hydraulics	Ψ	351.4527165	
electrical	θ	945.2762021	
Additional Information			
Engine: Rolls-Royce BR710 C4-11 turbofan	ENG	4009	lbs.
fuel capacity	FMXTOT	41300	lbs.
Max T-O Weight	TOGW	91,000	lbs.
altitude (max)	Amax	51000	ft
air density	ρair	3.64	slugs/ft^3
max speed	vmax	841.867	ft/s

#fuse eng	FNEF	2	
tot # eng	FNENG	2	
# wing eng	FNEW	0	
fuse planform area	FPAREA	180.8906	
thrust of each eng	FTHRST	15385	lbs.
aux fuel tanks	FULAUX	0	
fuel density ratio (not jet)	FULDEN	1	lbs./gal
factor for wing fuel cap	FWMAX	23	
hydr sys pressure	HYDPR	3000	psi
number of flight crew	NFLCR	3	
number of fuse	NFUSE	1	
number of galleys	NGALC	0	
number of passengers	NPASS	15	
#buisness pass	NPB	15	
#first class pass	NPF	0	
#tourist class pass	NPT	0	
# flight attendants	NSTU	1.375	
# fuel tanks	NTANK	2	
dive maneuver dyn press	QDIVE	0	psf
tot movable wing SA	SFLAP	2407	ft^2
wing span	SPAN	90.833333	ft
ref wing area	SW	4741.5	ft^2
quart chord sweep area	SWEEP	27	
weighted avg wing t/c	TCA	0.1	
taper ratio of wing	TR	0.26	
ult load factor	ULF	4.92	
wing var sweep factor	VARSWP	0	
max mach number	VMAX	0.885	
max fuse width	WF	7.3333333	ft
tot fuse length	XL	96.416667	ft
length of pass compartment	XLP	7.83	ft
taper ratio of wing	TR	0.26	
quart chord sweep area	SWEEP	4741.5	deg
weighted avg wing t/c	AR	7.36	
Max T-O weight	GW	91,000	lbs.
max fuel capacity in wing	FULWMX	41489	lbs.
max fuel cap in fuse	FULFMX	41489	lbs.
max cruise mach	VCMN	0.85	
max mach number	VMMO	0.885	
number of cargo containers	NCON	0	
cabin area	Acabin	42.236968	ft
dihedral angle	DIH	0	deg
aspect ratio of VT	ARVT	140.16	
taper ratio of VT	TRVT	0.233	

weight of baseline engine	WENG	4009	lb
fuel capacity in wing	FULWMX	476036.5	lb
fuel capacity in fueslage	FULFMX	-436471	lb
max landing approcah velocity	VAPPR	217.727	mph
max usable fuel weight	FUEMAX	41300	lb
ramp weight	RAMPWT	91400	lb
fixed OP empty weight	DOWE	48,300	lb
area of canard	SCAN	0	ft^2
ar of canard	ARCAN	0	
tr of canard	TRCAN	0	
sweep of VT	SWPVT	37	DEG
take off fuel flow	TAKOFF	1394	lb/hr/engine
length of main landing gear	XLMLG	14.333333	in
max landing length	FLLDG	2770	ft
weight per passenger	WPPASS	165	lbs.

A.Dassault Falcon 900 Aircraft Data

Aircraft Data (External)	**Symbol**	**Value**	**Unit**
Planform Area	Sref	527.4	ft^2
Takeoff Gross Weight	TOGW	45,500	lbs.
Operating Empty Weight	OEW	23,875	lbs.
Wetted Area	Swet	1108.763894	ft^2
Length	L	66.25	ft
Wing Span	b	63.41666667	ft
Taper Ratio*	λ	0.275	
Ahorizstab/Awing	Ahfp	0.272468714	
Avertstab/Awing	Avfp	0.200417141	
horiz stab planform area	Swfh	143.7	ft^2
vert stab planform area	Swfv	105.7	ft^2
Aspect Ratio	AR	7.6	
wing thickness to chord ratio*	t/c	0.12	
1/2 Swet	Stb	554.3819471	ft^2
Total Momentum Thrust *	Ttot	14250	lbf
Max Dynamic Pressure*	Qmax	1201581.974	psf
Ultimate Load Factor*	ULF	3.75	
Modifying Factor*	mf	0.95	
Engine Airflow* (mass flow rate)	Wa	143	lbs./s
# of Engines	Neng	3	
Thermal Protec. Weight*	Wins	0	lbs./ft^2
Equivalent Diameter*	Dbe	8.166666667	ft
Vehicle volume *	Vtot	1264	ft3
volumetric efficiency	ηvol	0.7	
tank density	ρtank		

Aircraft Data (Internal)	**Symbol**	**Value**	**Unit**
Wing span	B	63.416667	ft
baggage weight	BPP	44	lbs.
carrier based ac switch	CARBAS	0	
cargo carried in fuse (not bags)	CARGOF		lbs.
cargo carried in wing (not bags)	CARGOW		lbs.
atmospheric pressure ratio	DELTA	0.07138	
design range	DESRNG	4000	nmi
max fuse depth	DF	6.25	ft
design gross weight	DG	45,500	
max fuel capacity	FMXTOT	19165	lbs.
avg diam of eng	FNAC	3.283333	
#fuse eng	FNEF	3	
tot # eng	FNENG	3	
# wing eng	FNEW	0	
fuse planform area	FPAREA	171.01339	
thrust of each eng	FTHRST	4750	lbs.
aux fuel tanks	FULAUX	0	
fuel density ratio (not jet)	FULDEN	1	lbs./gal
factor for wing fuel cap	FWMAX	23	
hydr sys pressure	HYDPR	3000	psi
number of flight crew	NFLCR	2	
number of fuse	NFUSE	1	
number of galleys	NGALC	0	
number of passengers	NPASS	19	
#buisness pass	NPB	19	

tank volume	Vtank		
tank weight	Wtank	19165	
Height	h	24.75	ft
Sub weight values			
body	σ	24678.42401	
tail	Λ	411408829.6	
hydraulics	Ψ	247.5758054	
electrical	θ	608.5582705	
Additional Information			
Engine: Honeywell TFE731-20 turbofan	ENG	899	lbs.
fuel capacity	FMXTOT	19165	lbs.
Max T-O Weight	TOGW	45,500	lbs.
altitude (max)	Amax	51000	ft
air density	ρair	3.64	slugs/ft^3
max speed	vmax	812.533	ft/s

#first class pass	NPF	0	
#tourist class pass	NPT	0	
# flight attendants	NSTU	1.475	
# fuel tanks	NTANK	4	
dive maneuver dyn press	QDIVE	0	psf
tot movable wing SA	SFLAP	49.88	ft^2
wing span	SPAN	63.416667	ft
ref wing area	SW	527.4	ft^2
quart chord sweep area	SWEEP	29	
weighted avg wing t/c	TCA	0.12	
taper ratio of wing	TR	0.275	
ult load factor	ULF	3.75	
wing var sweep factor	VARSWP	0	
max mach number	VMAX	0.87	
max fuse width	WF	8.1666667	ft
tot fuse length	XL	66.25	ft
length of pass compartment	XLP	33.166667	ft
taper ratio of wing	TR	0.275	
quart chord sweep area	SWEEP	29	deg
weighted avg wing t/c	AR	7.6	
Max T-O weight	GW	45,500	lbs.
max cruise mach	VCMN	0.84	
max mach number	VMMO	0.87	
number of cargo containers	NCON	0	
cabin area	Acabin	52.381694	ft
dihedral angle	DIH	0	deg
aspect ratio of VT	ARVT	2.128666	
taper ratio of VT	TRVT	0.3	
weight of baseline engine	WENG	899	lb
fuel capacity in wing	FULWMX	10057.74	lb
fuel capacity in fueslage	FULFMX	7596.262	lb
max landing approach velocity	VAPPR	181.867	mph
max usable fuel weight	FUEMAX	19165	lb
ramp weight	RAMPWT	45700	lb
fixed OP empty weight	DOWE	23,875	lb
area of canard	SCAN	0	ft^2
ar of canard	ARCAN	0	
tr of canard	TRCAN	0	
sweep of VT	SWPVT	28	DEG
take off fuel flow	TAKOFF	875	lb/hr/engine
length of main landing gear	XLMLG	49.6875	in
max landing length	FLLDG	2375	ft
aspect ratio of HT	**ARHT**	**4.4861**	
taper ratio of HT	**TRHT**	**0.4**	

	WRATIO	0.4968464	
	FLAPR	0.0945772	
weight per passenger	WPPASS	165	lbs.

A. Learjet 45 Aircraft Data

Aircraft Data (External)	Symbol	Value	Unit
Planform Area	Sref	311.6	ft^2
Takeoff Gross Weight	TOGW	21,500	lbs.
Operating Empty Weight	OEW	12,850	lbs.
Wetted Area	Swet	666.3717679	ft^2
Length	L	58	ft
Wing Span	b	47.75	ft
Taper Ratio*	λ	0.507	
Ahorizstab/Awing	Ahfp	0.173299101	
Avertstab/Awing	Avfp	0.123234917	
horiz stab planform area	Swfh	54	ft^2
vert stab planform area	Swfv	38.4	ft^2
Aspect Ratio	AR	7.3	
wing thickness to chord ratio*	t/c	0.14	
1/2 Swet	Stb	333.1858839	ft^2
Total Momentum Thrust *	Ttot	7300	lbf
Max Dynamic Pressure*	Qmax	562358.3815	psf
Ultimate Load Factor*	ULF	3.75	
Modifying Factor*	mf	0.95	
Engine Airflow* (mass flow rate)	Wa	143	lbs./s
# of Engines	Neng	2	
Thermal Protec. Weight*	Wins	0	$lbs./ft^2$
Equivalent Diameter*	Dbe	3.607580999	ft
Vehicle volume *	Vtot	415	ft3
volumetric efficiency	ηvol	0.7	
tank density	ρtank		
tank volume	Vtank		
tank weight	Wtank	6062	
Height	h	14.08333333	ft
Sub weight values			
body	σ	14188.64758	
tail	Λ	60560249.56	
hydraulics	Ψ	162.9193109	
electrical	θ	404.64691	
Additional Information			
Engine: Honeywell TFE731-20 turbofan	ENG	899	lbs.
fuel capacity	FMXTOT	6062	lbs.
Max T-O Weight	TOGW	21,500	lbs.

Aircraft Data (Internal)	Symbol	Value	Unit
Wing span	B	47.75	ft
baggage weight	BPP	44	lbs.
carrier based ac switch	CARBAS	0	
cargo carried in fuse (not bags)	CARGOF	0	lbs.
cargo carried in wing (not bags)	CARGOW	0	lbs.
atmospheric pressure ratio	DELTA	0.07138	
design range	DESRNG	1710	nmi
max fuse depth	DF	5.75	ft
design gross weight	DG	21,500	
max fuel capacity	FMXTOT	6062	lbs.
avg diam of eng	**FNAC**	**5.08333**	
#fuse eng	FNEF	2	
tot # eng	FNENG	2	
# wing eng	FNEW	0	
fuse planform area	FPAREA	109.1406	
thrust of each eng	**FTHRST**	**3650**	**lbs.**
aux fuel tanks	FULAUX	0	
fuel density ratio (not jet)	FULDEN	1	lbs./gal
factor for wing fuel cap	FWMAX	23	
hydr sys pressure	HYDPR	3000	psi
number of flight crew	NFLCR	2	
number of fuse	NFUSE	1	
number of galleys	NGALC	0	
number of passengers	NPASS	8	
#buisness pass	NPB	8	
#first class pass	NPF	0	
#tourist class pass	NPT	0	
# flight attendants	NSTU	1.2	
# fuel tanks	NTANK	3	
dive maneuver dyn press	QDIVE	0	psf
tot movable wing SA	SFLAP	18.48	ft^2
wing span	SPAN	47.75	ft
ref wing area	SW	311.6	ft^2
quart chord sweep area	SWEEP	13	
weighted avg wing t/c	TCA	0.14	
taper ratio of wing	TR	0.507	
ult load factor	ULF	3.75	

altitude (max)	Amax	51000	ft
air density	ρair	3.64	slugs/ft^3
max speed	vmax	555.867	ft/s

wing var sweep factor	VARSWP	0	
max mach number	VMAX	0.81	
max fuse width	WF	7.3333333	ft
tot fuse length	XL	24.666667	ft
length of pass compartment	XLP	19.75	ft
taper ratio of wing	TR	0.507	
quart chord sweep area	SWEEP	13	deg
weighted avg wing t/c	AR	7.3	
Max T-O weight	GW	21,500	lbs.
max cruise mach	VCMN	0.69	
max mach number	VMMO	0.81	
number of cargo containers	NCON	0	
cabin area	Acabin	42.236968	ft
dihedral angle	DIH	2.5	deg
aspect ratio of VT	ARVT	0.6510417	
taper ratio of VT	TRVT	0.493	
weight of baseline engine	WENG	899	lb
fuel capacity in wing	FULWMX	5085.826	lb
fuel capacity in fueslage	FULFMX	1892.174	lb
max landing approcah velocity	VAPPR	236.293	mph
max usable fuel weight	FUEMAX	6062	lb
ramp weight	RAMPWT	20750	lb
fixed OP empty weight	DOWE	12,850	lb
area of canard	SCAN	0	ft^2
ar of canard	ARCAN	0	
tr of canard	TRCAN	0	
sweep of VT	SWPVT	40	DEG
take off fuel flow	TAKOFF	875	lb/hr/engine
length of main landing gear	XLMLG	3.34	in
max landing length	**FLLDG**	**2660**	**ft**
aspect ratio of HT	**ARHT**	**6.26963**	
taper ratio of HT	**TRHT**	**0.4**	
	WRATIO	0.893023	
	FLAPR	0.0593068	
weight per passenger	WPPASS	165	lbs.

Appendix D: W&B Detailed Verification Results

B. Concorde

FLOPS Concorde		
MASS AND BALANCE SUMMARY	**LBS**	**% of Total**
WING	23749	15.56

W&B Weight Breakdown	
Component	**Weight (lbs.)**
Total Structure [Wstr]	**71,988.89**
Body [Wb]	44,346.00

HORIZONTAL TAIL	0	0
VERTICAL TAIL	1992	1.31
VERTICAL FIN	0	0
CANARD	0	0
FUSELAGE	23636	15.48
LANDING GEAR	15048	9.86
NACELLE (AIR INDUCTION)	4747	3.11
Total Structure [Wstr]	**69173**	**45.32**
ENGINES	28000	18.34
THRUST REVERSERS	0	0
MISCELLANEOUS SYSTEMS	1712	1.12
FUEL SYSTEM-TANKS AND PLUMBING	3102	2.03
Total Propulsion [Wprop]	**32814**	**21.5**
SURFACE CONTROLS	3367	2.21
AUXILIARY POWER	947	0.62
INSTRUMENTS	1394	0.91
HYDRAULICS	2441	1.6
ELECTRICAL	3884	2.54
AVIONICS	2842	1.86
FURNISHINGS AND EQUIPMENT	23614	15.47
AIR CONDITIONING	4016	2.63
ANTI-ICING	279	0.18
Total Subsystem [Wsub]	**42785**	**28.03**
CREW AND BAGGAGE-FLIGHT, 5	1125	0.74
-CABIN, 4	620	0.41
UNUSABLE FUEL	1294	0.85
ENGINE OIL	311	0.2
PASSENGER SERVICE	3471	2.27
CARGO CONTAINERS	1050	0.69
OPERATING ITEMS TOTAL	7871	
Total Operating Items [Wopi]	**152643**	**100**
PASSENGERS, 128	21120	13.84
PASSENGER BAGGAGE	5632	3.69
CARGO	0	0
Total Payload Items [Wpay]	**26752**	
ZERO FUEL WEIGHT	179395	117.53
Total Fuel Capacity [Wfuelcap]	**209605**	**137.32**
WEIGHT EMPTY	**144772**	**94.84**
RAMP (GROSS) WEIGHT	**389000**	**254.84**

Wing [Ww]	7,434.40
Vertical Fin [Wfinv]	575.14
Horizontal Fin [Wfinh]	-
Thermal Protection [Wtps]	73.05
Landing Gear [Wgear]	18,540.00
Thrust Structure [Wthrst]	1,020.30
Ballast [Wballast]	-
Total Propulsion [Wprop]	**71,988.89**
Engine [Wttr]	39,890.00
Tank [Wtank]	12,547.00
Total Subsystem [Wsub]	**36,138.69**
Surface Controls [WSC]	6,262.20
Auiliary Poweer Unit [WAPU]	588.12
Instruments [WIN]	154.29
Hydraulics [WHYD]	1,168.30
Electrical [WELEC]	3,528.90
Avionics [WAVONC]	270.18
Furnishings & Equip [WFURN]	17,186.00
Air Conditioning [WAC]	3,140.00
Anti-Icing [WAI]	3,840.70
Total Operating Items [Wopi]	**4,448.95**
Flight Att & Galley & Bags [WSTUAB]	155.00
Flight Crew & Bags [WFLCRB]	450.00
Unusable Fuel [WUF]	1,293.70
Engine Oil [WOIL]	311.25
Passenger Service [WSRV]	2,239.00
Cargo Containers [WCON]	-
Total Payload Items [Wpay]	**27,170.00**
Passengers [WPASS]	21,450.00
Passenger Baggage [WPBAG]	5,720.00
Cargo [WCARGO]	-
Total Fuel Capacity [Wfuelcap]	**189,830.00**
Wing Fuel Capacity [FULWMX]	145,797.00
Fuse Fuel Capacity [FUFU]	189,830.00
Max Fuel Capacity [FMXTOT]	172,083.00
Zero fuel Weight [WZF]	199,170.00
Fuel Weight [FUELM]	189,830.00
OWE (lbs.) =	**192,183.52**
Total Weight (lbs.) =	**382,013.52**
% ERROR	**1.82886**

Percent Error 0

C. Tupolev 144 - LL

FLOPS Tu-144 LL		
MASS AND BALANCE SUMMARY	**LBS**	**% of Total**
WING	30401	15.4
HORIZONTAL TAIL	0	0
VERTICAL TAIL	3032	1.54
VERTICAL FIN	0	0
CANARD	1499	0.76
FUSELAGE	38973	19.75
LANDING GEAR	11073	5.61
NACELLE (AIR INDUCTION)	7835	3.97
Total Structure [Wstr]	**92813**	**47.02**
ENGINES	34400	17.43
THRUST REVERSERS	0	0
MISCELLANEOUS SYSTEMS	2323	1.18
FUEL SYSTEM-TANKS AND PLUMBING	3167	1.6
Total Propulsion [Wprop]	**39890**	**20.21**
SURFACE CONTROLS	4682	2.37
AUXILIARY POWER	1095	0.55
INSTRUMENTS	2102	1.07
HYDRAULICS	4345	2.2
ELECTRICAL	4370	2.21
AVIONICS	3765	1.91
FURNISHINGS AND EQUIPMENT	29246	14.82
AIR CONDITIONING	5992	3.04
ANTI-ICING	342	0.17
Total Subsystem [Wsub]	**55939**	**28.34**
CREW AND BAGGAGE-FLIGHT, 5	1125	0.57
-CABIN, 4	620	0.31
UNUSABLE FUEL	1625	0.82
ENGINE OIL	395	0.2
PASSENGER SERVICE	3741	1.9
CARGO CONTAINERS	1225	0.62
Total Operating Items [Wopi]	**197373**	**100**
PASSENGERS, 128	23100	11.7
PASSENGER BAGGAGE	6160	3.12
CARGO	0	0

W&B Weight Breakdown	
Component	**Weight (lbs.)**
Total Structure [Wstr]	**101921.32**
Body [Wb]	64482.65
Wing [Ww]	8607.65
Vertical Fin [Wfinv]	838.63
Horizontal Fin [Wfinh]	0.00
Thermal Protection [Wtps]	8570.99
Landing Gear [Wgear]	17977.40
Thrust Structure [Wthrst]	1444.00
Ballast [Wballast]	0.00
Total Propulsion [Wprop]	**43057.11**
Engine [Wttr]	39890.11
Fuel system [WFSYS]	3166.99
Total Subsystem [Wsub]	**46041.60**
Surface Controls [WSC]	4255.50
Auiliary Poweer Unit [WAPU]	871.81
Instruments [WIN]	835.19
Hydraulics [WHYD]	2121.81
Electrical [WELEC]	4012.48
Avionics [WAVONC]	955.18
Furnishings & Equip [WFURN]	26429.50
Air Conditioning [WAC]	6355.38
Anti-Icing [WAI]	204.74
Total Operating Items [Wopi]	**5100.00**
Flight Att & Galley & Bags [WSTUAB]	155.00
Flight Crew & Bags [WFLCRB]	450.00
Unusable Fuel [WUF]	1580.43
Engine Oil [WOIL]	395.47
Passenger Service [WSRV]	2519.11
Cargo Containers [WCON]	0.00
Total Payload Items [Wpay]	**31350.00**
Passengers [WPASS]	24750.00
Passenger Baggage [WPBAG]	6600.00
Cargo [WCARGO]	0.00
Total Fuel Capacity [Wfuelcap]	**209440.00**
Wing Fuel Capacity [FULWMX]	197659.63
Fuse Fuel Capacity [FUFU]	11780.37
Max Fuel Capacity [FMXTOT]	209440.03
Zero fuel Weight [WZF]	251810.00

Total Payload Items [Wpay]	**29260**	**14.82**
ZERO FUEL WEIGHT	226633	114.82
Total Fuel Capacity [Wfuelcap]	**184992**	**93.72**
WEIGHT EMPTY	**188641**	**95.58**
RAMP (GROSS) WEIGHT	**410000**	**207.73**
Percent Error	**0**	

Fuel Weight [FUELM]	209440.00
OWE (lbs.) =	**227470.02**
Total Weight (lbs.) =	**436910.02**
% ERROR	6.1592

D.Gulfstream G550

FLOPS Gulfstream G550

MASS AND BALANCE SUMMARY	**LBS**	**% of Total**
WING	8071	19.12
HORIZONTAL TAIL	0	0
VERTICAL TAIL	0	0
VERTICAL FIN	0	0
CANARD	0	0
FUSELAGE	6881	16.3
LANDING GEAR	3647	8.64
NACELLE (AIR INDUCTION)	1543	3.66
Total Structure [Wstr]	**20143**	**47.72**
ENGINES	8018	19
THRUST REVERSERS	0	0
MISCELLANEOUS SYSTEMS	428	1.01
FUEL SYSTEM-TANKS AND PLUMBING	658	1.56
Total Propulsion [Wprop]	**9103**	**21.57**
SURFACE CONTROLS	897	2.13
AUXILIARY POWER	463	1.1
INSTRUMENTS	437	1.04
HYDRAULICS	608	1.44
ELECTRICAL	1469	3.48
AVIONICS	1692	4.01
FURNISHINGS AND EQUIPMENT	4359	10.33
AIR CONDITIONING	718	1.7
ANTI-ICING	158	0.37
Total Subsystem [Wsub]	**10800**	**25.59**
CREW AND BAGGAGE-FLIGHT, 4	900	2.13
-CABIN, 1	155	0.37
UNUSABLE FUEL	299	0.71
ENGINE OIL	86	0.2

W&B Weight Breakdown

Component	**Weight (lbs.)**
Total Structure [Wstr]	**20142.00**
Body [Wb]	6881.00
Wing [Ww]	8071.00
Vertical Fin [Wfinv]	0.00
Horizontal Fin [Wfinh]	0.00
Thermal Protection [Wtps]	0.00
Landing Gear [Wgear]	3647.00
Thrust Structure [Wthrst]	1543.00
Ballast [Wballast]	0.00
Total Propulsion [Wprop]	**8676.00**
Engine [Wttr]	8018.00
Fuel system [WFSYS]	658.00
Total Subsystem [Wsub]	**10801.00**
Surface Controls [WSC]	897.00
Auiliary Poweer Unit [WAPU]	463.00
Instruments [WIN]	437.00
Hydraulics [WHYD]	608.00
Electrical [WELEC]	1469.00
Avionics [WAVONC]	1692.00
Furnishings & Equip [WFURN]	4359.00
Air Conditioning [WAC]	718.00
Anti-Icing [WAI]	158.00
Total Operating Items [Wopi]	**2161.00**
Flight Att & Galley & Bags [WSTUAB]	155.00
Flight Crew & Bags [WFLCRB]	900.00
Unusable Fuel [WUF]	299.00
Engine Oil [WOIL]	86.00
Passenger Service [WSRV]	546.00
Cargo Containers [WCON]	175.00
Total Payload Items [Wpay]	**3971.00**
Passengers [WPASS]	3135.00
Passenger Baggage [WPBAG]	836.00

PASSENGER SERVICE	546	1.29
CARGO CONTAINERS	175	0.41
Total Operating Items [Wopi]	**42208**	**100**
PASSENGERS, 19	3135	7.43
PASSENGER BAGGAGE	836	1.98
CARGO	0	0
Total Payload Items [Wpay]	**3971**	
ZERO FUEL WEIGHT	46179	109.41
Total Fuel Capacity [Wfuelcap]	**44821**	**106.19**
WEIGHT EMPTY	**40046**	**94.88**
RAMP (GROSS) WEIGHT	**91000**	**215.6**
Percent Error	**0**	

Cargo [WCARGO]	0.00
Total Fuel Capacity [Wfuelcap]	**41300.00**
Wing Fuel Capacity [FULWMX]	30000.00
Fuse Fuel Capacity [FUFU]	11300.00
Max Fuel Capacity [FMXTOT]	41599.00
Zero fuel Weight [WZF]	46179.00
Fuel Weight [FUELM]	41300.00
OWE (lbs.) =	**45751.00**
Total Weight (lbs.) =	**87051.00**
% ERROR	**4.54**

E. Dassault Falcon 900

FLOPS Dassault Falcon 900

MASS AND BALANCE SUMMARY	LBS	% of Total
WING	3011	13.83
HORIZONTAL TAIL	0	0
VERTICAL TAIL	0	0
VERTICAL FIN	0	0
CANARD	0	0
FUSELAGE	4170	19.15
LANDING GEAR	1652	7.59
NACELLE (AIR INDUCTION)	251	1.15
Total Structure [Wstr]	**9084**	**41.72**
ENGINES	2697	12.39
THRUST REVERSERS	0	0
MISCELLANEOUS SYSTEMS	265	1.22
FUEL SYSTEM-TANKS AND PLUMBING	499	2.29
Total Propulsion [Wprop]	**3461**	**15.9**
SURFACE CONTROLS	320	1.47
AUXILIARY POWER	433	1.99
INSTRUMENTS	315	1.45
HYDRAULICS	428	1.97
ELECTRICAL	1574	7.23
AVIONICS	881	4.05
FURNISHINGS AND EQUIPMENT	2979	13.68
AIR CONDITIONING	521	2.39
ANTI-ICING	122	0.56

W&B Weight Breakdown

Component	Weight (lbs.)
Total Structure [Wstr]	**9084.00**
Body [Wb]	4170.00
Wing [Ww]	3011.00
Vertical Fin [Wfinv]	0.00
Horizontal Fin [Wfinh]	0.00
Thermal Protection [Wtps]	0.00
Landing Gear [Wgear]	1652.00
Thrust Structure [Wthrst]	251.00
Ballast [Wballast]	0.00
Total Propulsion [Wprop]	**3196.00**
Engine [Wttr]	2697.00
Fuel system [WFSYS]	499.00
Total Subsystem [Wsub]	**7573.00**
Surface Controls [WSC]	320.00
Auiliary Power Unit [WAPU]	433.00
Instruments [WIN]	315.00
Hydraulics [WHYD]	428.00
Electrical [WELEC]	1574.00
Avionics [WAVONC]	881.00
Furnishings & Equip [WFURN]	2979.00
Air Conditioning [WAC]	521.00
Anti-Icing [WAI]	122.00
Total Operating Items [Wopi]	**1653.00**
Flight Att & Galley & Bags [WSTUAB]	155.00
Flight Crew & Bags [WFLCRB]	450.00

Total Subsystem [Wsub]	**7574**	**34.79**
CREW AND BAGGAGE-FLIGHT, 2	450	2.07
-CABIN, 1	155	0.71
UNUSABLE FUEL	326	1.5
ENGINE OIL	60	0.28
PASSENGER SERVICE	487	2.24
CARGO CONTAINERS	175	0.8
Total Operating Items [Wopi]	**21772**	**100**
PASSENGERS, 19	3135	14.4
PASSENGER BAGGAGE	836	3.84
CARGO	0	0
Total Payload Items [Wpay]	**3971**	
ZERO FUEL WEIGHT	25743	118.24
Total Fuel Capacity [Wfuelcap]	**19760**	**90.76**
WEIGHT EMPTY	**20119**	**92.41**
RAMP (GROSS) WEIGHT	**45503**	**208.99**
Percent Error	**0.006593**	

Unusable Fuel [WUF]	326.00
Engine Oil [WOIL]	60.00
Passenger Service [WSRV]	487.00
Cargo Containers [WCON]	175.00
Total Payload Items [Wpay]	**3971.00**
Passengers [WPASS]	3135.00
Passenger Baggage [WPBAG]	836.00
Cargo [WCARGO]	0.00
Total Fuel Capacity [Wfuelcap]	**19160.00**
Wing Fuel Capacity [FULWMX]	10057.70
Fuse Fuel Capacity [FUFU]	7596.30
Max Fuel Capacity [FMXTOT]	17980.00
Zero fuel Weight [WZF]	25743.00
Fuel Weight [FUELM]	19160.00
OWE (lbs.) =	**25477.00**
Total Weight (lbs.) =	**44637.00**
% ERROR	**1.93**

F. Learjet 45

FLOPS Learjet 45

MASS AND BALANCE SUMMARY	**LBS**	**% of Total**
WING	1249	12.19
HORIZONTAL TAIL	0	0
VERTICAL TAIL	0	0
VERTICAL FIN	0	0
CANARD	0	0
FUSELAGE	946	9.24
LANDING GEAR	568	5.55
NACELLE (AIR INDUCTION)	130	1.27
Total Structure [Wstr]	**2894**	**28.25**
ENGINES	1798	17.55
THRUST REVERSERS	0	0
MISCELLANEOUS SYSTEMS	169	1.65
FUEL SYSTEM-TANKS AND PLUMBING	228	2.22
Total Propulsion [Wprop]	**2195**	**21.42**
SURFACE CONTROLS	137	1.33
AUXILIARY POWER	296	2.89
INSTRUMENTS	150	1.47

W&B Weight Breakdown

Component	**Weight (lbs.)**
Total Structure [Wstr]	**2893.00**
Body [Wb]	946.00
Wing [Ww]	1249.00
Vertical Fin [Wfinv]	0.00
Horizontal Fin [Wfinh]	0.00
Thermal Protection [Wtps]	0.00
Landing Gear [Wgear]	568.00
Thrust Structure [Wthrst]	130.00
Ballast [Wballast]	0.00
Total Propulsion [Wprop]	**2026.00**
Engine [Wttr]	1798.00
Fuel system [WFSYS]	228.00
Total Subsystem [Wsub]	**3951.00**
Surface Controls [WSC]	137.00
Auiliary Poweer Unit [WAPU]	296.00
Instruments [WIN]	150.00
Hydraulics [WHYD]	155.00
Electrical [WELEC]	779.00
Avionics [WAVONC]	505.00
Furnishings & Equip [WFURN]	1602.00

HYDRAULICS	155	1.51
ELECTRICAL	779	7.6
AVIONICS	505	4.93
FURNISHINGS AND EQUIPMENT	1602	15.64
AIR CONDITIONING	242	2.36
ANTI-ICING	85	0.83
Total Subsystem [Wsub]	**3951**	**38.56**
CREW AND BAGGAGE-FLIGHT, 2	450	4.39
-CABIN, 1	155	1.51
UNUSABLE FUEL	198	1.93
ENGINE OIL	34	0.33
PASSENGER SERVICE	194	1.89
CARGO CONTAINERS	175	1.71
Total Operating Items [Wopi]	**10245**	**100**
PASSENGERS, 9	1485	14.49
PASSENGER BAGGAGE	360	3.51
CARGO	0	0
Total Payload Items [Wpay]	**1845**	
ZERO FUEL WEIGHT	12090	118.01
Total Fuel Capacity [Wfuelcap]	**8615**	**84.09**
WEIGHT EMPTY	**9040**	**88.23**
RAMP (GROSS) WEIGHT	**20705**	**202.1**
Percent Error	**3.83965**	

Air Conditioning [WAC]	242.00
Anti-Icing [WAI]	85.00
Total Operating Items [Wopi]	**1206.00**
Flight Att & Galley & Bags [WSTUAB]	155.00
Flight Crew & Bags [WFLCRB]	450.00
Unusable Fuel [WUF]	198.00
Engine Oil [WOIL]	34.00
Passenger Service [WSRV]	194.00
Cargo Containers [WCON]	175.00
Total Payload Items [Wpay]	**1845.00**
Passengers [WPASS]	1485.00
Passenger Baggage [WPBAG]	360.00
Cargo [WCARGO]	0.00
Total Fuel Capacity [Wfuelcap]	**6978.00**
Wing Fuel Capacity [FULWMX]	5085.80
Fuse Fuel Capacity [FUFU]	1892.20
Max Fuel Capacity [FMXTOT]	7176.00
Zero fuel Weight [WZF]	12090.00
Fuel Weight [FUELM]	6978.00
OWE (lbs.) =	**11921.00**
Total Weight (lbs.) =	**18899.00**
% ERROR	**13.76**

Appendix E: Method Cards

A.Weights & Balances Method Cards

Method Overview				
Discipline: Weights & Balances	**Design Phase:** Configuration Layout	**Method Title:** Component Weight Estimation	**Categorization:** Semi-Empirical	**Author:** Renazco, R.
Reference: Douglas P, Bryce L Horvath, and Linwood A McCullers. "The Flight Optimization System Weights Estimation Method - FLOPS." Technical Memorandum. National Aeronautics and Space Administration, June 2017. (WATE) Harloff, Gary J, and Brian M Berkowitz. "HASA-Hypersonic Aerospace Sizing Analysis for the Preliminary Design of Aerospace Vehicles." *NASA*, 1988, 60.				
Brief Description:				

Generate detailed weight breakdown of each component; used to set internal layout, design Center of Gravity and static margin range for use in sizing control effectors.	
Assumption: Manned Passenger or Cargo Aircraft Missing parameters: Concorde	**Applicability:** Sub-sonic to Hypersonic Transport Vehicles
Execution of Method	
Input: - Design Trade Data - Trajectory & Performance Data concerning mission/flight profile - Thermal Protection System average weight per area - Synthesis Design Point - Propulsion System Specs - Geometric Vehicle Dimensions	
Analysis Description: - Calculates structures components such as the body and wing - Propulsion System - Systems & Equipment - Operational Items - PAX systems	
Output: Component weight breakdown	

Experience		
Accuracy: Depends on inputs, verification aircraft yielded low error ~ 4.34 %	**Time to Calculate:** 0.4 seconds	**General Comment:** Converted to function for use in Fenix Sizing HASA – External WATE – Internal

Method Overview				
Discipline: Weights & Balances	**Design Phase:** Configuration Layout & Configuration Evaluation	**Method Title:** CG Determination	**Categorization:** Analytical	**Author:** Renazco, R.
Reference: None				
Brief Description: Each component considered a point mass where the moments of inertia of the vehicle are determined given the position of said components centroids as X, Y, Z coordinates. Moments of inertia and weights are used to determine the total Center of Gravity (CG).				
Assumption: Symmetry across X-axis	**Applicability:** Subsonic – Hypersonic Vehicles			

Execution of Method		
Input: Detailed weight breakdown Iterated internal layout – component locations Fuel tank capacities & number		
Analysis Description: Calculate moment arms of each component Non-dimensionalize all values Calculate Moment of Inertia along each axis Calculate CG & re-dimensionalize		
Output: Center of gravity of vehicle		
Experience		
Accuracy: 100 % accuracy	**Time to Calculate:** t < 0.1 seconds	**General Comment:** Iterated to design internal layout for desired CG/CG shift range

Method Overview				
Discipline: Weights & Balances	**Design Phase:** Configuration Evaluation	**Method Title:** CG Shift Range Determination	**Categorization:** Analytical	**Author:** Renazco, R. Hoofard, M. Khammash, O.
Reference: None				
Brief Description: Determines the possible range of CG movement by shifting fuel around the vehicle				
Assumption: Powerful pumps Fuel slosh negligible Liquid fuel	**Applicability:** Subsonic – Hypersonic Vehicles			
Execution of Method				
Input: Internal layout Point in trajectory & fuel percent in tanks Tank number & capacities Propellant specifications				

Analysis Description: Shifts all fuel to foremost position filling up tanks in front of vehicle and emptying tanks at rear. Calculates min. CG position Shifts all fuel to rearmost position filling up tanks in rear of vehicle and emptying tanks at front. Calculates max CG position
Output: Static margin range of CG shifting – used by S&C to size control effectors

Experience

Accuracy:	**Time to Calculate:**	**General Comment:**
100%	t < 0.1 seconds	Possibly add of ballast if needed

B. Synthesis Method Cards

Method Overview

Discipline:	**Design Phase:**	**Method Title:**	**Categorization:**	**Author:**
Synthesis	Parametric Sizing	Weight and Volume Budget Convergence	Semi-Empirical Analytical	Czysz, P.

References:
Coleman, G., "Aircraft conceptual design - an adaptable parametric sizing methodology"
Czysz, P. et al., "Future Spacecraft Propulsion Systems and Integration"

Brief Description:
Estimate the weight and volume of the vehicle components based on technology level to create weight and volume budgets that are converged by iterating planform area.

Assumption:	**Applicability:**
Components are based on technology level.	Transonic to Hypersonic Vehicles

Execution of Method

Input:
Slenderness, Planform Area and Take-off Gross Weight guesses, Structural Index, Wetted-to-Planform Area Ratio, Systems Weight and Volume, Crew Weight and Volume, Payload Weight and Volume, Propulsion System Weight and Volume, Propellant Volume and Density, Weight Ratio

Analysis Description:
Calculate weight and volume budgets and iterate planform area until convergence.

$$OEW = \frac{I_{str}K_w S_{pln} + C_{sys} + W_{cprv} + W_{prop}(W_{pay} + W_{crew})}{\frac{1}{1+\mu_a} - f_{sys} - W_{prop}}$$

$$OWE = \frac{\tau \cdot S_{pln}^{1.5}(1 - k_{vv} - k_{vs}) - \not{V}_{fix} - \not{V}_{crew} - \not{V}_{pay}}{V_{ppl} + V_{prop}}$$

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

Solve for new *TOGW*

$TOGW = OWE \cdot WR$

Output:
Take-off Gross Weight, Operating Weight Empty, Operating Empty Weight, Planform Area

Experience

Accuracy:	**Time to Calculate:**	**General Comment:**
Within ±10%	Dependent on guess values	Was verified using Sänger EHTV and Concorde

Method Overview

Discipline:	**Design Phase:**	**Method Title:**	**Categorization:**	**Author:**
Synthesis Propulsion	Parametric Sizing	Propulsion Sizing	Empirical Analytical	Park, N.

References:
Czysz, P. et al., "Future Spacecraft Propulsion Systems and Integration"

Brief Description:
Determine the number of engines required and the total weight fraction of the propulsion system and the density of the propulsion system and it's required propellant.

Assumption:	**Applicability:**
Aerodynamic performance based on empirical surrogate vehicle(s).	Transonic to Hypersonic Vehicles

Execution of Method

Input:
Planform Area, Take-off Gross Weight, Fuel Fraction
Thrust-to-Weight required for take-off or Maximum Drag
Thrust, Weight, and Volume per Engine
Fuel Density
For rockets: Oxidizer density and Oxidizer-to-Fuel Ratio

Analysis Description:

$$WR = \frac{1}{1 - ff}$$

Iterate through list of engines

$T_{req} = (T/W)_{TO} \cdot TOGW$ or $T_{req} = C_{Dmax} \cdot q|_{CDmax} \cdot S_{pln}$

$T_{avail} = N_{eng} \cdot T_{SL}$ or $T_{avail} = N_{eng} \cdot T|_{CDmax}$

Iterate N_{eng} until $T_{avail} \geq T_{req}$

$$W_{prop} = \frac{N_{eng} \cdot W_{eng}}{TOGW/WR}$$

$$\not{V}_{prop} = \frac{N_{eng} \cdot \not{V}_{eng}}{TOGW/WR}$$

$$\rho_{ppl} = \frac{\rho_{fuel}(1 + OFR)}{1 + OFR\left({}^{\rho_{fuel}}/_{\rho_{oxidizer}}\right)}$$

For non-combined turbo-rocket:

$$\forall_{ppl} = \frac{\frac{1}{1 - ff_t} - 1}{\rho_{fuel,t}} + \frac{\frac{1}{1 - ff_r} - 1}{\rho_{ppl}}$$

Else:

$$\forall_{ppl} = \frac{WR - 1}{\rho_{ppl}}$$

Output:
Weight Fraction of propulsion system
Propulsion system density

Experience		
Accuracy: Dependent on accuracy of performance constraints	**Time to Calculate:** Dependent on number of engines in candidate list	**General Comment:** To be used with Fenix Sizing

Function Card		
Discipline: Synthesis	**Name:** Sizing	**Author:** Park, N.

Assumptions: Technology Level Structural Index Aerodynamic performance based on surrogate vehicle Engine volume estimated as a cylinder	**Applicability:** Transonic to Hypersonic vehicles

Inputs

Variables:	Units/Valid Range:
Slenderness: tau	0.4 – 0.24
Planform Area guess: S_pln	m^2
Take-off Gross Weight guess: TOGW	kg
Number of Passengers: N_PAX	-
Payload Weight: W_pay	kg
Structural Index: I_str	kg/m^2
Passenger or Cargo switch: ConfigType	0 = PAX, 1 = Cargo
Rocket or Turbo-Rocket switch: PropType	0 = Rocket, 1 = Turbo-Rocket

Outputs

Variables:	Units:
Slenderness: tau	-
Planform Area guess: S_pln	m^2
Take-off Gross Weight guess: TOGW	kg

Operating Weight Empty: OWE Operating Empty Weight: OEW Number of Airbreathing Engines: N_eng Number of Rocket Engines: N_rkteng Fuel Weight Fraction: ff Thrust per Engine: T_eng Payload Weight: W_pay Propellant Volume: V_ppl Industry Capability Index: ICI	kg kg - - - N kg m^3 -
Comments: Aerodynamic and Trajectory information in workspace file: Fenix_Mission	

Function Card		
Discipline: Synthesis	**Name:** Fenix Sizing	**Author:** Park, N.

Assumptions: Technology Level Structural Index Planform Area and Take-off Gross Weight guesses Passenger or Payload Range	**Applicability:** Transonic to Hypersonic vehicles
Inputs	
Variables: Lower Slenderness Limit: Tau1 Upper Slenderness Limit: Tau2 Passenger or Cargo switch: ConfigType Rocket or Turbo-Rocket switch: PropType	**Units/Valid Range:** 0.4 – 0.24 0.4 – 0.24 0 = PAX, 1 = Cargo 0 = Rocket, 1 = Turbo-Rocket
Outputs	
Variables: Parametric Sizing Data Array: PS • Slenderness Array: TAU • Take-off Gross Weight Array: TOGW_ • Operating Weight Empty Array: OWE_ • Operating Empty Weight Array: OEW_ • Planform Area Array: SPLN • Number of Passengers Array: NPAX • Fuel Fraction Array: FF • Number of Airbreathing Engines: NENG • Number of Rocket Engines: NRKT • Thrust per Engine Array: TENG • Payload Weight Array: WPAY • Propellant Volume Array: VPPL	**Units:** - - kg kg kg m^2 - - - - N kg m^3
Comments: Iterates Sizing function and saves data to plot solution space	

Function Card		
Discipline: Synthesis Aerodynamics Geometry/Structures	**Name:** FenixLayout	**Authors:** Plihon, A. Park, N.

Assumptions:	**Applicability:** Only applicable to Fenix mission and geometry

Inputs

Variables:	**Units/Valid Range:**
Passenger or Cargo switch: ConfigType	0 = PAX, 1 = Cargo
Rocket or Turbo-Rocket switch: PropType	0 = Rocket, 1 = Turbo-Rocket
Index of the Parametric Sizing Array: iteration	-
Parametric Sizing Data Array: PS	-

Outputs

Variables:	**Units:**
Configuration Layout Data Array: CL	-
• Frontal Area: FA	m^2
• Height of Cabin: HCabin	m
• Width of Cabin: WCabin	m
• Length of Cabin: LCabin	m
• Width of Aisle: WAisle	m
• Length of Cockpit: Lcockpit	m
• Cabin Radius: CabinRad	m
• Total Cabin Height: TotalCabinHeight	m
• Height of Baggage Storage Area: HBag	m
• Volume of Cabin: Vcab	m3
• Length of Nose: Lcool	m
• Length of Nacelle: Lcowl	m
• Length from nose to cowl lip: Linlet	m
• Height of Nacelle: Hcowl	m
• Length of Nozzle: Lnoz	m
• Height of Nozzle: Hnoz	m
• Length of Fuel Storage Area: Lfuel	m
• Height of Rocket Mounting Area: Hrocket	m
• Percent Height of CG Location: zCGpercent	-
• TPS thickness: TPS_t	m
• Width of Fuselage: W	m
• Total Volume of Geometry: VtotGeo	m3
• Wetted Area: Swet	m2
• Length of Vehicle: Length	m
• Fore Sweep Angle: Sweep1	°
• Aft Sweep Angle: Sweep2	°
• Aspect Ratio: ARmin	-
• Span: Span	m
• Stall Velocity: V_stall	m/s

• Area of Vertical Tail: Svt	m2
• Height of Vertical Tail: Hvt	m
• Vertical Tail Root Chord Length: CrVT	m
• Vertical Tail Tip Chord Length: CtVT	m
• Vertical Tail Leading-Edge Sweep Angle: SweepVT	°
• Volume of the Wing: Vwing	m3
• Maximum Vertical Tail Thickness: tvt	m
• Fuselage Area: Sfus	m2
• Wing Area: Swing	m2
• Volume Error between Layout and Sizing: ErrorVol	%
• Frontal Area Ratio: FAR	-
Comments: Cycles through Parametric Sizing data to create layouts of the configurations for use in Autom8 script	

Appendix F: Code

A. W&B Weight Estimation & Inertias Code V4

B. Synthesis Saenger Verification Code

C. Synthesis Supersonic AC Verification Code

D. Synthesis Configuration Layout Code V4

E. Geo Support Code (Centroid)

Appendix G: Results

A. W&B Optimized Vehicles Detailed Weight Breakdowns

Optimal Airbreather Design

PAX	36
Tau	0.11

W&B Weight Breakdown

Component	Weight (lbs.)
Total Structure [Wstr]	**140902.08**
Body [Wb]	37875.20
Wing [Ww]	7958.72
Vertical Fin [Wfinv]	2853.62
Horizontal Fin [Wfinh]	0.00
Thermal Protection [Wtps]	78146.20
Landing Gear [Wgear]	8415.22

Optimal Rocket Design

PAX	44
Tau	0.09

W&B Weight Breakdown

Component	Weight (lbs.)
Total Structure [Wstr]	**142163.56**
Body [Wb]	41137.80
Wing [Ww]	7129.76
Vertical Fin [Wfinv]	2760.56
Horizontal Fin [Wfinh]	0.00
Thermal Protection [Wtps]	79686.20
Landing Gear [Wgear]	11380.38

Thrust Structure [Wthrst]	5653.12	Thrust Structure [Wthrst]	68.86
Ballast [Wballast]	0.00	Ballast [Wballast]	0.00
Total Propulsion [Wprop]	**1894.81**	**Total Propulsion [Wprop]**	**658.00**
Engine [Wttr]	1458.72	Engine [Wttr]	0.00
Fuel system [WFSYS]	436.09	Fuel system [WFSYS]	658.00
Total Subsystem [Wsub]	**20844.11**	**Total Subsystem [Wsub]**	**24977.94**
Surface Controls [WSC]	2876.94	Surface Controls [WSC]	3892.68
Auiliary Poweer Unit [WAPU]	375.68	Auiliary Poweer Unit [WAPU]	413.85
Instruments [WIN]	357.12	Instruments [WIN]	299.88
Hydraulics [WHYD]	402.62	Hydraulics [WHYD]	490.47
Electrical [WELEC]	1986.93	Electrical [WELEC]	1469.00
Avionics [WAVONC]	488.15	Avionics [WAVONC]	521.52
Furnishings & Equip [WFURN]	10319.98	Furnishings & Equip [WFURN]	13019.82
Air Conditioning [WAC]	4019.40	Air Conditioning [WAC]	4853.42
Anti-Icing [WAI]	17.29	Anti-Icing [WAI]	17.29
Total Operating Items [Wopi]	**3122.98**	**Total Operating Items [Wopi]**	**2221.79**
Flight Att & Galley & Bags [WSTUAB]	154.67	Flight Att & Galley & Bags [WSTUAB]	154.67
Flight Crew & Bags [WFLCRB]	449.06	Flight Crew & Bags [WFLCRB]	449.06
Unusable Fuel [WUF]	1041.11	Unusable Fuel [WUF]	722.50
Engine Oil [WOIL]	888.58	Engine Oil [WOIL]	0.00
Passenger Service [WSRV]	589.55	Passenger Service [WSRV]	720.56
Cargo Containers [WCON]	0.00	Cargo Containers [WCON]	175.00
Total Payload Items [Wpay]	**8636.74**	**Total Payload Items [Wpay]**	**10555.94**
Passengers [WPASS]	7056.06	Passengers [WPASS]	8624.00
Passenger Baggage [WPBAG]	1580.68	Passenger Baggage [WPBAG]	1931.94
Cargo [WCARGO]	0.00	Cargo [WCARGO]	0.00
Total Fuel Capacity [Wfuelcap]	**127167.11**	**Total Fuel Capacity [Wfuelcap]**	**202792.50**
Wing Fuel Capacity [FULWMX]	83930.29	Wing Fuel Capacity [FULWMX]	133843.05
Fuse Fuel Capacity [FUFU]	43236.82	Fuse Fuel Capacity [FUFU]	68949.45
Max Fuel Capacity [FMXTOT]	128208.22	Max Fuel Capacity [FMXTOT]	203515.00
Fuel Weight [FUELM]	127167.11	Fuel Weight [FUELM]	202792.50
OWE (lbs.) =	**175400.71**	**OWE (lbs.) =**	**180577.23**
Total Weight (lbs.) =	**302567.82**	**Total Weight (lbs.) =**	**383369.73**

Appendix H: Raw Data Output

A. Supersonic Transport FLOPS Optimization

B. Concorde FLOPS Generations v1

C. Tu-144 LL FLOPS Generations v3

D. Gulfstream G550 FLOPS Generation

E. Dassault Falcon 900 FLOPS Generation

F. Learjet 45 FLOPS Generation

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