Development of Advanced Commercial Transport Aircraft Configurations Through the Assessment of Past, Present, and Future Technologies

Amit Oza, Gary Coleman, Lex Gonzalez, Bernd Chudoba

Mechanical and Aerospace Engineering Department
University of Texas at Arlington

Paul Czsyz

Hypertech Concepts LLC

Abstract

NASA's *Subsonic Fixed Wing Project* has organized its research portfolio into three areas; N+1 represents concepts and technologies for the next generation B737/A320 sized transports; N+2 represents hybrid-wing-body concepts and related technologies; N+3 represents subsonic and supersonic concepts and technologies beyond hybrid-wing-body in the 2025+ timeframe. The initiation of this study by the NASA Langley Research Center is timely given the historically significant changes currently being witnessed with: (1) *technology* (configuration, materials, propulsion), (2) *economics* (rising energy costs), (3) *social* (mobility), (4) *environmental* (noise, emissions, fuel consumption), (5) *market* (return on investment, job stability). Consequently, the historically established air transportation projections of transport capacity growth may become obsolete, thereby demanding a paradigm-shift towards future robust air transportation scenarios. Thereby the United States must be prepared to lead this *Air Transportation Revolution* by timely delivering industry technology solutions throughout the air transportation continuum.

Introduction

The principal objectives of this study are as follows:
To perform advanced strategic planning for N+3 commercial transport aircraft concepts and technologies (large long haul) to assist technologists, researchers, and managers at NASA LaRC, NIA, and other US centers in decision-making.
To transition such selected technology portfolio into future operational and practical industry hardware applications.

As such, the effort is limited to the formulation and first-order application of a systematic product development life-cycle methodology. A generic methodology has been developed to support research portfolio planning and its execution for *evolutionary* and *revolutionary* N+3 generation commercial subsonic large long haul aircraft concepts and associated with past, present, and future technologies.

This study investigated in total 5 case studies for 5 unique technology portfolios, 1 market segments (Boeing B777-300ER, 335 PAX), and 2 design scenarios (variable altitude, fixed altitude [27 kft]). Primary technologies under consideration included (Reference 1):

N+0
Tail-aft configuration
Aluminum structure, high bypass turbofan, partial laminar aerodynamics.

N+1
Tail-aft configuration
Composite structure, next generation high bypass turbofan, increased laminar aerodynamics.

N+2
Thrust vector control
Composite structure, next generation high bypass turbofan with thrust vectoring capability, increased laminar aerodynamics.

Blended wing body
Composite structure, next generation high bypass turbofan, increased laminar aerodynamics.

N+3
Tail-aft configuration + strut-braced wing
Composite structure, next generation high bypass turbofan, natural laminar aerodynamics.

Tail-aft configuration + truss-braced wing
Composite structure, next generation high bypass turbofan, natural laminar aerodynamics.

Consequently the sizing process developed for this project has demonstrated the robustness to consistently assess configuration and technology options to allow more informed decision-making. The case studies themselves did prioritize technology benefit matrix at the technology level.

Overall Study Methodology

The study has been organized into three distinct phases with individual work elements or tasks defined for each:

Phase I Preparatory Activities (Reference 2)

Task 1 – Research Strategy Definition
Objective is to formulate, discuss, harmonize, and adopt research ground rules for the 12 month study. Particular emphasis is directed towards collaboration with the main three NASA LaRC organizations: APPO, SACD, and RTD.

Task 2 – Operational Requirements Definition
This task primarily interacts with NASA LaRC APPO and SACD. The objective is to define generic operational aircraft mission requirements to be expected in the 2025+ timeframe. This requires defining a range of likely mission scenarios, from today's transportation mission to tomorrow's transportation revolution.

Task 3 – Reference Vehicle Definition
Appropriate reference aircraft need to be selected for the mission requirements. Those vehicle(s) serve as the datum to which any development needs to be compared to.

Task 4 – Disciplinary Technology Matrix
This task primarily interacts with NASA LaRC RTD. Past, present, and future disciplinary technologies are surveyed, organized, and documented with the expectation towards completeness. A technology matrix emerges as a working document, representing the current state-of-the-art understanding available.

Task 5 – Multi-Disciplinary Configuration Matrix
This task primarily interacts with NASA LaRC SACD and RTD. Multi-disciplinary past, present, and future aircraft configurations and concepts are defined, surveyed, and documented in this matrix. Throughout Tasks 4 and 5 two grouping schemes emerge which allow a consistent characterization of technologies and arbitrary aircraft configurations and their subassemblies. The main benefit of this categorization materializes when utilized as a 'virtual design-toolbox'. Each subassembly can be assigned to a set of physical characteristics. Then, different configuration- and concept-scenarios (outside the box) can be explored first order assuming different levels of technology for a given mission specification.

The outcome of Phase I will be a report documenting Tasks 1 to 5, including meeting protocols and a detail plan for the remainder of the 12 month research study.

Phase II Configuration, Concept and Technology Identification

Task 6 – Disciplinary Technology Potential
This task primarily interacts with NASA LaRC RTD. The objective is to assess the disciplinary development limits theoretically possible. This will define for each discipline (e.g., aerodynamics) an equivalent to the 'minimum energy limit line'. Questions that need to be asked

include "what is the minimum drag possible, maximum L/D possible, smallest wetted surface area possible, etc". This task challenges the technologist to first identify the physical limit and then to review the options as to how to access the idling performance potential assuming risk from low (could be) to high (might be).

Task 7 – Parametric Sizing (PS) Phase
This task primarily interacts with NASA LaRC SACD and RTD. The conceptual design (CD) phase can be conveniently subdivided into three distinct sub-phases: (a) Parametric Sizing (PS) Phase [technical and economic design solution space identification], (b) Configuration Layout (CL) Phase [identification of alternative design solutions resulting in configuration trade matrix], and (c) Configuration Evolution (CE) Phase [quantification and identification of baseline aircraft]. Tasks 7 and 8 are only concerned with the first two CD phases, being the PS and CL phases. The PS (Parametric Sizing) Phase first identifies the available solution space for the given mission specification. This solution space is, at this point, not yet populated by distinct point designs, but it rather identifies the feasibility of the mission by assuming a specific technology level.

Task 8 – Configuration Layout (CL) Phase
This task primarily interacts with NASA LaRC SACD and RTD. The two matrices from Tasks 4 and 5 are utilized to the full during the CL (Configuration Layout) Phase. The CL Phase represents the true 'outside the box' creative opportunity, which identifies an array of competing design solutions which are located inside the solution space. Sensitivity studies are the primary means to identify the potential of individual technologies, aircraft configurations and concepts.

The report deliverable for Phase II documents Tasks 6 to 8. Transparency is provided as to how technology, configuration and concept sensitivities are generated. The main research effort needs to be invested into Tasks 7 and 8.

Phase III Advanced Planning Activities

Task 9 – Prioritized Technology Matrix
This task primarily interacts with NASA LaRC RTD. The technology matrix generated during Task 4 collects, interprets, and implements the research results (technology sensitivities leading to prioritization) generated throughout Phase II.

Task 10 – Prioritized Configuration Matrix
This task primarily interacts with NASA LaRC SACD. The configuration matrix generated during Task 5 collects, interprets, and implements the research results (technology sensitivities leading to prioritization) generated throughout Phase II.

Task 11 – Demonstration of Configuration Evaluation (CE) Phase
This task primarily interacts with NASA LaRC APPO, SACD, and RTD. The AVD Lab next

generation life-cycle synthesis methodology AVDS is demonstrated with an advanced design case study. The relevance of this ‘design control center’ to all three NASA LaRC organizations is emphasized. The conceptual design level design case study covers the complete simulated life-cycle from mission definition to accident investigation.

Task 12 – Strategic Recommendations
The deliverables of the 12 month effort are guidelines defined for (a) technology planning, (b) configuration planning, (c) concept planning. Justification is provided throughout leading to prioritized recommendations.

Data-Base, Knowledge-Base and Parametric Process

A key component enabling the development of revolutionary transport aircraft is effective management of the knowledge-generation and knowledge-preservation activity. As illustrated before, the research approach implemented places emphasis on elevating the understanding with regards to project aims and objectives, overall resulting in an informed and structured approach. In the present context, the research challenge is best formulated with the question: How to efficiently synchronize the *understanding available* with the *understanding required* to specify an *evolutionary* and *revolutionary* N+3 generation commercial subsonic large long haul aircraft concept with the technical resources, team support and time available? Due to the limited timeframe available, the DB and KB assistances have become indispensable to expedite the learning process.

The following two sub-chapters present the flight vehicle conceptual design data-base (DB) and knowledge-base (KB) as developed and utilized for the present research undertaking. The main flight vehicle research & design work is directly benefitting from this dedicated DB & KB foundation.

Flight Vehicle Data-Base

The first step in efficiently utilizing existing aircraft design knowledge has been a systematic literature survey, which in itself has been an ongoing effort throughout the existence of the *AVD Laboratory* and of course during the current research period. Source for accessing normal and radical design data and knowledge have been (a) public domain literature, (b) institution and company internal sources, and (c) expert advice. For efficient handling of design related data and information, a dedicated computer-based aircraft conceptual design data-base (DB) has been set up, see Figure 1. Reference 3 presents the literature DB file-structure. This system handles disciplinary and inter-disciplinary literature relevant for conceptual design (methodologies, flight mechanics, aerodynamics, etc.), interview-protocols, flight vehicle case study information (descriptive-, historical-, numerical information on conventional and unconventional flight vehicle configurations), simulation and flight test information, etc. The overall requirement for the creation of the DB has been simplicity in construction, maintenance, and operation, to comply with the underlying time constraints.

A detailed description of the DB is beyond the scope of the present discussion. The system has become a steadily growing, comprehensive, and effective working tool. Clearly, the quality of such system is only as good as the degree of completeness, actuality, and familiarity by the user. The DB has matured to be the central instrument for managing aircraft design data and information. However, the true potential of this system for utilizing design data and information has been opened up by proceeding as follows:

1. availability of a *reference list* containing meaningful entries; (*DB*)
2. availability of these references as a *hardcopy* on the table; (*DB*)
3. utilization of time to *absorb* the data & information; (*DB*)
4. *review, select, classify, subtract, and document* the data & information provided; (*DB*)
5. *extraction, combination and utilization* of data/ information in a pre-defined manner. (*KB*)

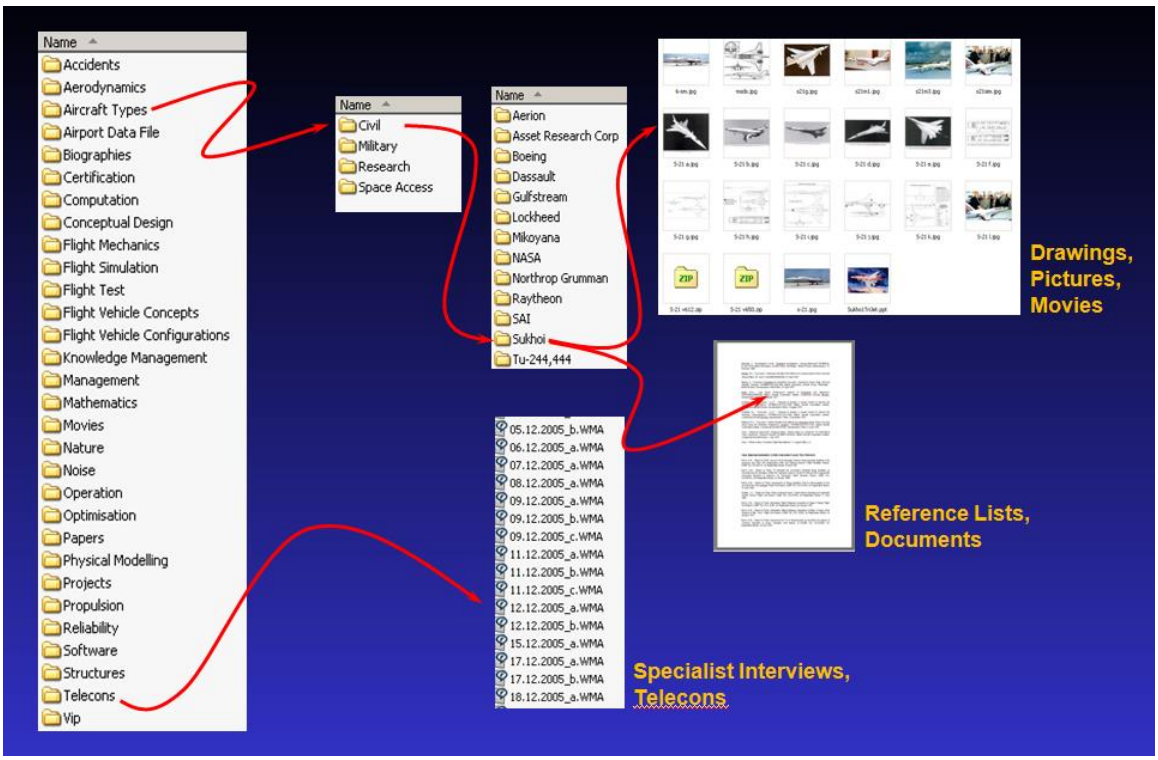

Figure 1. Dedicated AVD Laboratory DB and organization scheme. (Reference 1)

The first four steps are handled within the DB. The DB has been put to use to provide in an intermediate step (step four) suitably selected, structured, and condensed flight vehicle conceptual design data and information. The research goal, to develop an *evolutionary* and *revolutionary* N+3 generation commercial subsonic large long haul transport, requires to account for as many design-related interactions as necessary, since the rationale for the evolution of aircraft is diverse as a quick browse through aviation history reveals. The aircraft design disciplines identified relevant and the representative case studies of design ingenuity selected both elements need to be appreciated mutually, to efficiently serve the design understanding where innovation provided answers to otherwise troublesome problems. The updated DB embodies a technology-baseline attained, which is considered state-of-the-art for the current research undertaking.

Flight Vehicle Knowledge-Base

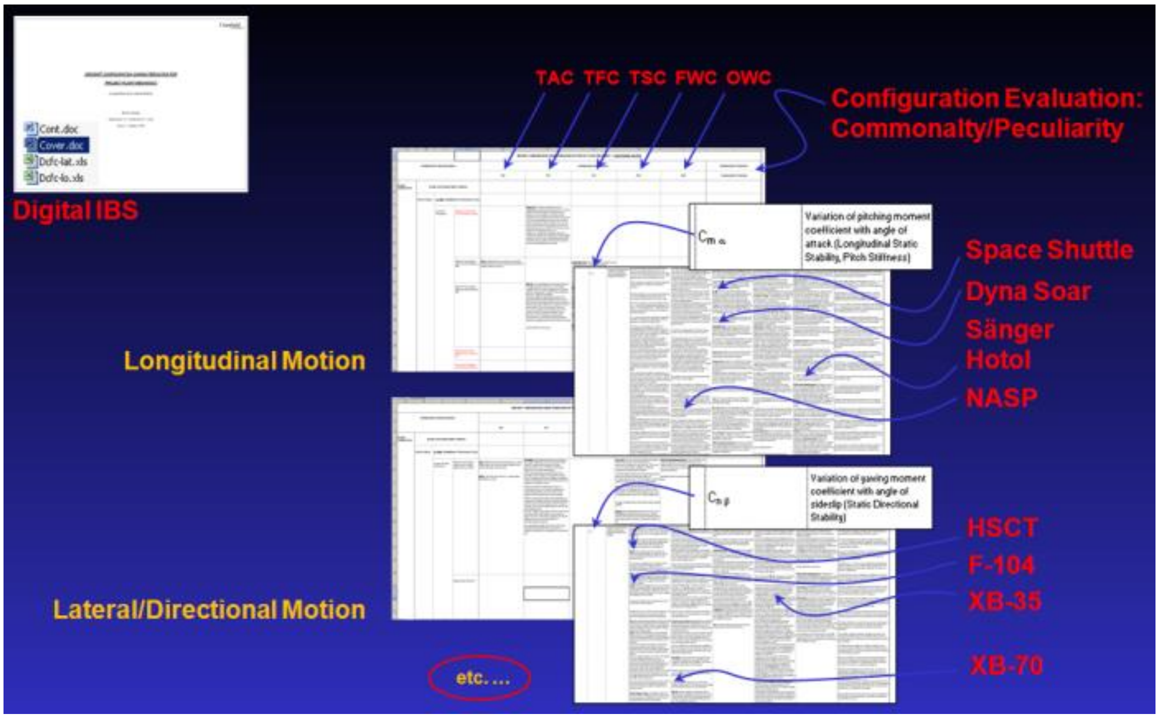

Figure 2. Design lessons-learned of selected design case-studies. (Reference 4)

The aircraft conceptual design knowledge-base (KB), as advanced and utilized for the present research undertaking, has to be considered an early development-version of a fully operational design knowledge-based system (KBS). Without reiterating the capability of exemplary KBSs, the KB system utilized here is a 'manual' system in contrast to the ideally automated KBS. However, independent on the degree of automation, both systems have in common that knowledge itself is the focus and that the knowledge acquisition activity is recognized as being one of the most problematic areas of KBS development. Clearly, it is the knowledge collecting, knowledge management and knowledge utilization activity, where the priorities for the present flight vehicle conceptual design KB have been laid due to time constraints imposed.

The primary objective of developing the dedicated aircraft conceptual design KB has been, to make relevant normal and radical design knowledge effortlessly available. The particular strength of the system manifests, in that it enables the user to advance his/her understanding with respect to the variety of legacy aircraft configurations by identifying aircraft configuration commonalties and peculiarities. This feature has been empowered by placing particular emphasis on consistently grouped flight vehicle configuration-specific design knowledge. As a result, design detail, for example longitudinal stability, can be compared between the range of aircraft configurations. This approach finally enables a reliable and trust-worthy generic aircraft configuration parameter identification process.

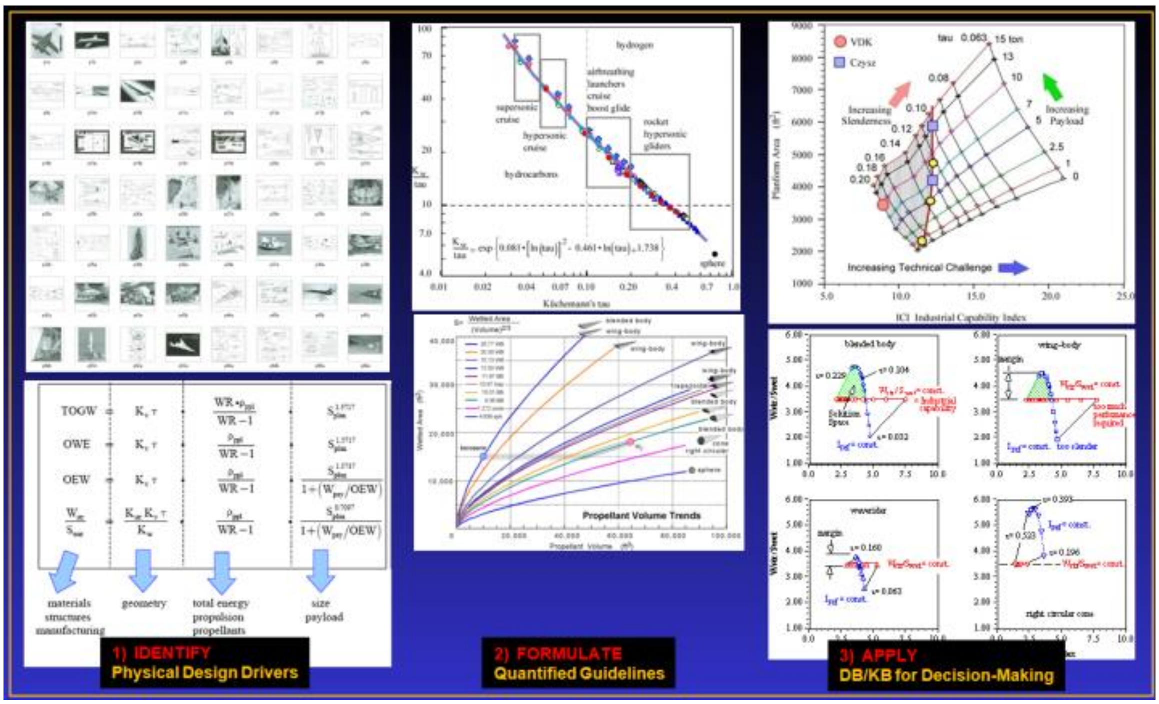

Figure 3. KB development steps resulting in numerical design guidelines. (Reference 4)

Figure 2 overviews the lessons-learned section as described above. This section clearly emphasizes on physical understanding and design related decision-making of relevant aircraft case studies.

Figure 3 introduces the steps required to arrive at knowledge-derived numerical design guidelines. At first, intimate technical understanding of pertinent design case studies enables the identification of gross design-drivers and variables with significant impact on the overall design. Those gross design drivers then form the basis for the underlying sizing relations in the sizing methodology. The resulting numerical design guidelines represent a true continuum of the pertinent design characteristic in contrast to the narrow exposure of typical point-design characteristics.

The ‘living-character’ of the DB and KB is ensured by permitting unconstrained data & knowledge entries as gained during the iterative design life-cycle.

In summary, the dedicated aircraft DB and KB have both matured towards fully integrated design support domains. The AVD Laboratory is routinely utilizing the project-specific DB and KB in concert with the process domain (sizing methodology), see Figure 4.

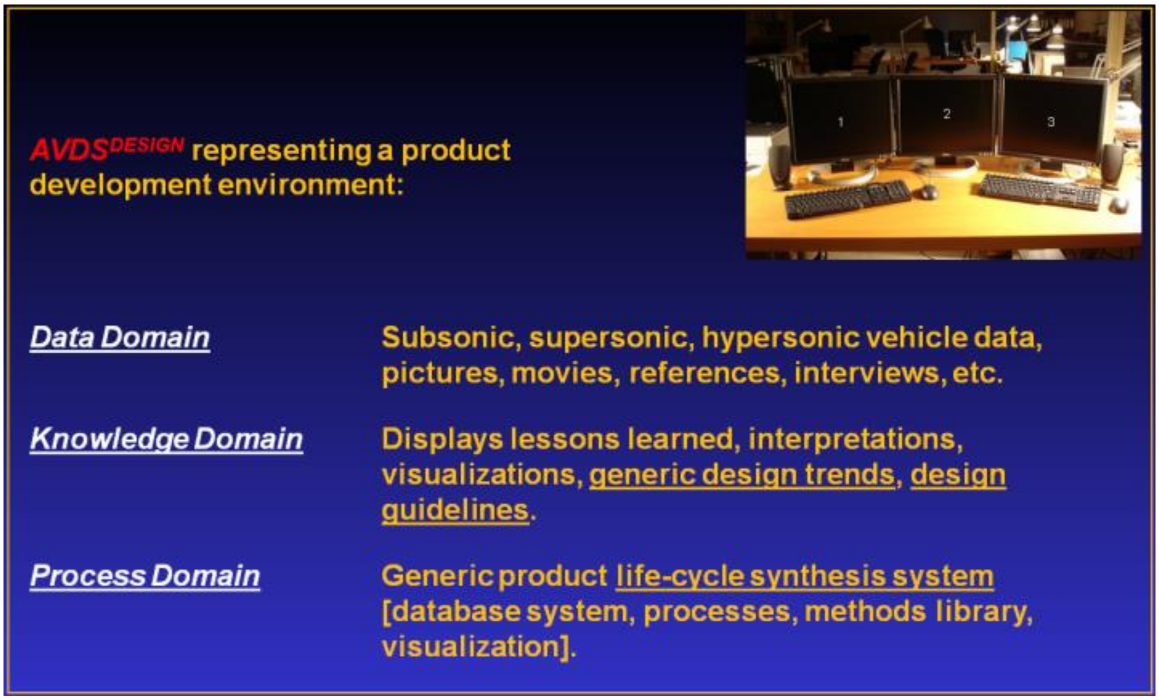

Figure 4. Integration scheme of data domain, knowledge domain, and process domain. (Reference 1)

AVD Sizing Process

AVD^{sizing} is a constant mission sizing process capable of first-order solution space screening of a wide variety of conventional and unconventional vehicle configurations. Solution space screening implies an overall focus on visualizing multi-disciplinary design interactions and trends. AVD^{sizing} is based on the *Hypersonic Convergence* sizing approach for transonic to hypersonic vehicle applications as developed at formerly McDonnell Aircraft Company between 1970 and 1990, see Reference 5. The modular process implemented with AVD^{sizing} relies upon a robust disciplinary methods library for analysis and a unique multi-disciplinary analysis (MDA) sizing logic and software kernel enabling data storage, design iterations, and process convergence. The integration of the disciplinary methods library and the generic multi-disciplinary sizing logic enables the consistent evaluation and comparison of radically different flight vehicles, see References 6, 7. The flight vehicle configuration independent implementation of AVD^sizing allows for rapid parametric exploration of the complete flight vehicle system via a convergence check to mission. Figure 5 visualizes the top level sizing process implemented.

At the heart of the process is the weight and balance budget. The results from the geometry, performance constraint and trajectory modules (weight ratio, required T/W ratio, and vehicle geometry) are provided to a weight & volume available and required logic. For a given vehicle slenderness parameter$\left(\tau = V_{total}/S_{pln}^{1.5}\right)$, the planform area is iterated through the total design process until weight & volume available equal weight & volume required.

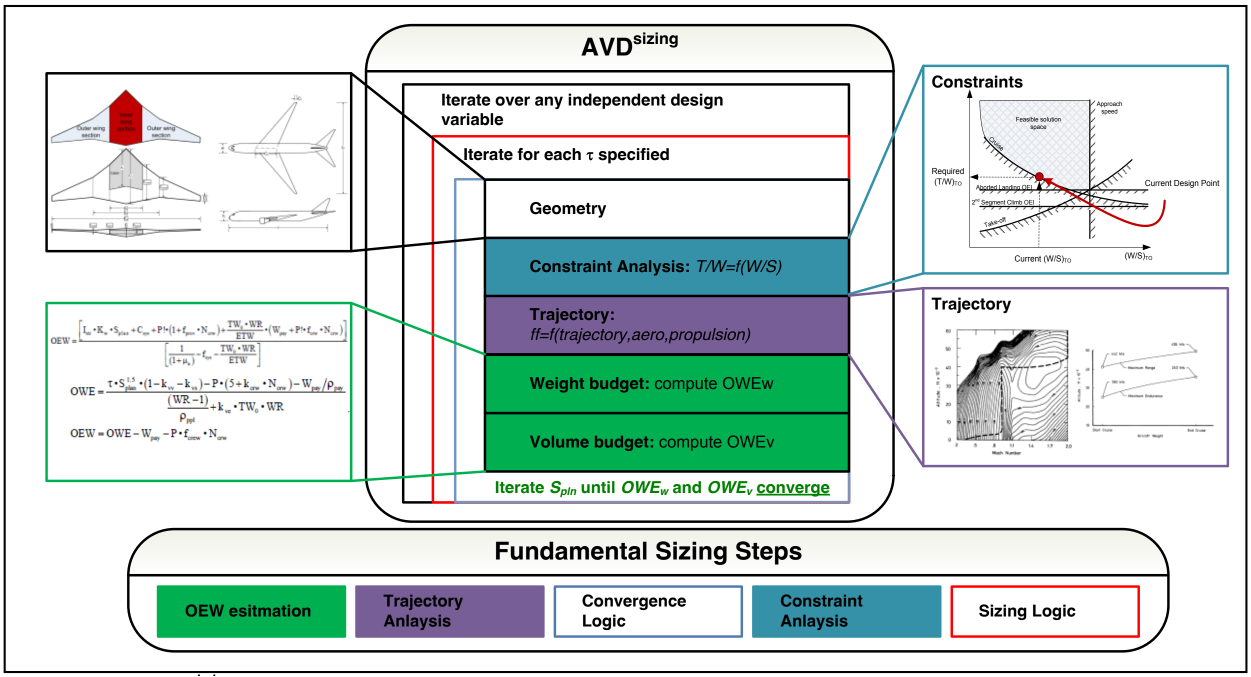

Figure 5. AVD^sizing methodology visualized via Nassi-Schneidermann structogram. (Reference 8)

N+n Technology Matrix and Design Mission

This study investigated in total 6 case studies for 6 unique technology portfolios (Table 1), 1 market segments (Boeing B777-300ER, 335 PAX), and 2 design scenarios (variable altitude, fixed altitude [27 kft]). Primary technology packages included, Reference 7:

N+0 (Baseline for comparison)
Tail-aft configuration
Aluminum structure, high bypass turbofan, partial laminar aerodynamics.

N+1
Tail-aft configuration

Composite structure, next generation high bypass turbofan, increased laminar aerodynamics.

N+2
Thrust vector control
Composite structure, next generation high bypass turbofan with thrust vectoring capability, increased laminar aerodynamics.

Blended wing body
Composite structure, next generation high bypass turbofan, increased laminar aerodynamics.

N+3
Tail-aft configuration + strut-braced wing
Composite structure, next generation high bypass turbofan, natural laminar aerodynamics.

Tail-aft configuration + truss-braced wing
Composite structure, next generation high bypass turbofan, natural laminar aerodynamics.

Table 1. N+n Technology Level Assumption Summary (Reference 1)

	N+0	**N+1**	**N+2**	**N+3**
Structures and Material	Aluminum primary structure with some composite secondary structure	Primarily Composite primary and secondary structure - 15% reduction in structural weight	Same as N+1	Mainly composite primary and secondary structure -Externally braced wings for thin natural laminar flow airfoils -Empirical correction factors based on VT studies
Propulsion	Available high-bypass turbofans EX: GE90, SFC_{cruise}=0.56	Next Generation high-bypass turbofans EX: B787, Genx SFC_{cruise}=0.502	Same as N+1	Same as N+1

Aerodynamics	Conventional wing design techniques	Improved laminar flow airfoils with - $Re_x = 4.95 \times 10^6$	Integrated winglet (BWB) - Effective aspect ratio = 1.1	Thin Natural laminar flow wing and fuselage combinations -Laminar flow Rex from F-14 wing glove experiment -Hoerner method for interference drag
Passenger Comfort	Standard cabin pressure (8,000 ft equivalent pressure) and passenger volume (approx 2.0 m3 / PAX for a 3 class cabin)	Increase passenger comfort cabin pressure (6,000 ft equivalent pressure) and passenger volume (approx 2.4 m^3 / PAX)	Same as N+1	Same as N+1
Configuration(s)	Tail Aft	Tail Aft	Thrust Vector Control Blended Wing Body	Strut-Braced Wing Truss-Braced Wing

Design Mission

The N+0 Boeing B777-300ER baseline is evaluated using the published formal design mission; Table 2. AVD^{sizing} is utilized to derive the required (1) geometry, (2) weight, (3) thrust and wing location to satisfy (a) the mission, (b) minimum direct operating cost and (c) statically stability with a static margin of, $0.05 < SM < 0.10$. This mission definition has been used for each vehicle configuration.

There are two design scenarios which have been considered; (1) Variable cruise altitude, and (2) Fixed cruise altitude. The first case solves for the altitude corresponding to cruise at max L/D for each step through the cruise phase. This is analogous to a cruise-climb trajectory for commercial aircraft. The second case has a fixed cruise altitude of 27 kft. The lower cruise altitude is an environmental benefit, due to reduced cirrus cloud formation from aircraft contrails.

Table 2. Design Mission - Boeing B777-300 ER (Reference 1)

Mission requirements	
Crew weight	
Crew (1-Captin, 1-1st officer, 14 cabin attendents)	1472 kg (3,250 lbs)
Payload weight	
Maximum (175 lbs passenger + 40 lbs cargo)	69853 kg (154,000 lbs)

370 pax (3-cabin), 33,770 kg cargo	
Design Passengers (325 pax, 6,474 kg cargo)	38168 kg (84,150 lbs)
Range	
Design	14075 km (8,000 nm)
Velocity	
Design Cruise Speed	0.85 M
Take-off field length (TOGW)	< 3,048 m (1,000 ft)
Landing field length (max landing weight)	< 1,767 m (5,780 ft)
Fuel reserves	926 km (500 nm)

Design Study Results

Variable Cruise Altitude (Figure 6)

N+1 Results

- The composite aircraft provides reduced DOC and fuel burn while increasing passenger comfort.
- This passenger comfort level will be used in N+2 and N+3
- Due to this, composite materials will be utilized in N+2 and N+3 configurations

N+2 Results

- While both the BWB and TVC provide an aerodynamic benefit the BWB gains greater performance through a structural weight reduction
- The BWB has the capability for ~15% improvement in DOC over N+1 and could meet the fuel burn reduction requirements of the N+2 initiative (~50 % relative to current technology, N+0)
- TVC demonstrates ~10% improvement in DOC over N+1 while requiring extensive R&D and certification challenges
- BWB approaches the N+2 fuel burn objective of 50%

N+3 Results

- Comparison of N+3, N+2, N+1 relative to N+0 baseline; the laminar flow TBW shows the greatest potential of performance & cost improvements
- TBW currently provides marginal improvement of SBW
- TBW and SBW approach the N+3 fuel burn objective of 75%

Fixed Cruise Altitude - 27 kft (Figure 7)

Mission changes from baseline B777 mission

- Cruise Altitude - 27 kft (8.2 km) maximum cruise altitude
- Cruise velocity - Constant 480 kts. Resulting in a cruise mach number of ~ 0.81 M

General disciplinary design impacts

- Geometry - Slight reduction in wing sweep due to the lower design mach number
- Propulsion - increased in SFC
- Aerodynamics - the $(W/S)_{TO}$ required for cruise at 27 kft at or near L/D_{max} is typically lower than the $(W/S)_{TO}$ required for approach. Therefore, the aircraft will cruise at a C_L lower then $C_{L(L/Dmax)}$

N+n Results

- The TBW and SBW performance is reduced due the significant reduction in cruise L/D
- The TBW/SBW cruise altitude reduces from ~55 kft to 27 kft
- TAC,TVC,BWB cruise altitude reduces from ~33 kft to 27 kft
- Results: TBW and SBW suffer the most from reduction in cruise altitude
- TBW and SBW still out perform TAC, TVC, and BWB

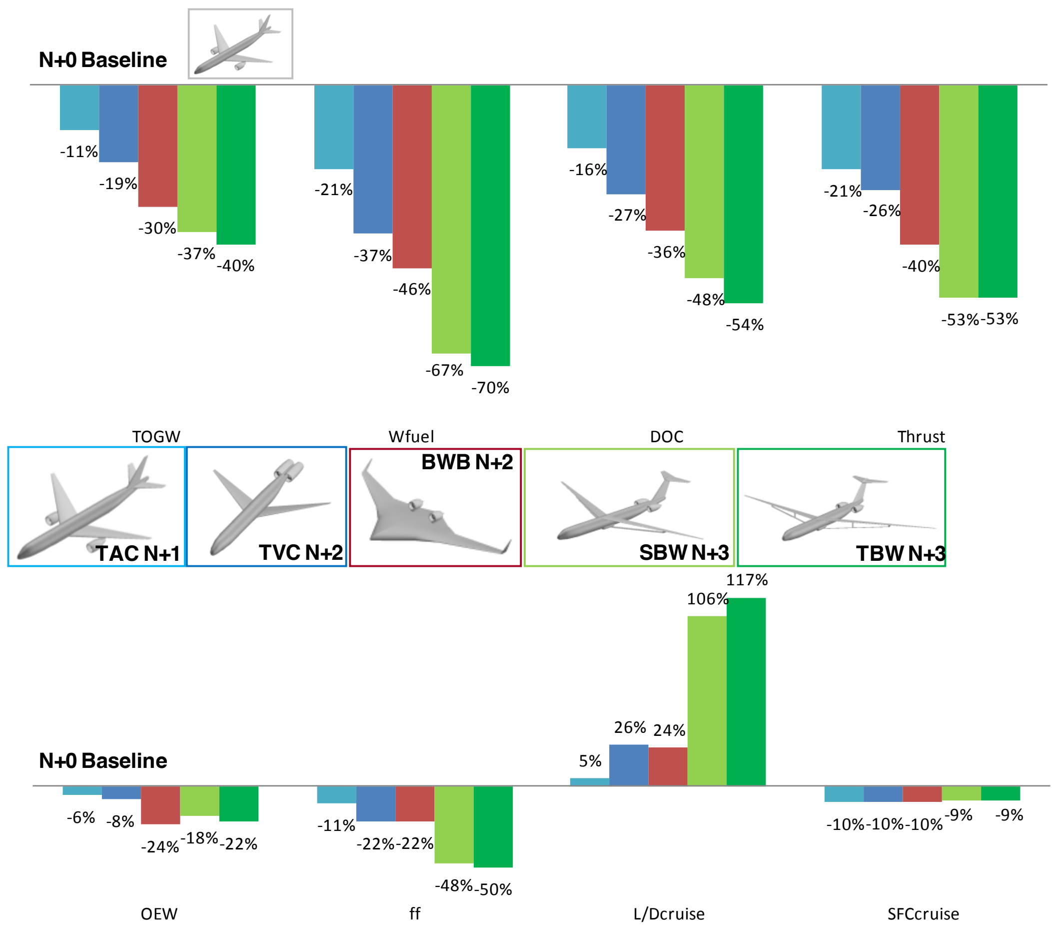

Figure 6. N+n Design Study Results - Variable Cruise Altitude (Reference 1)

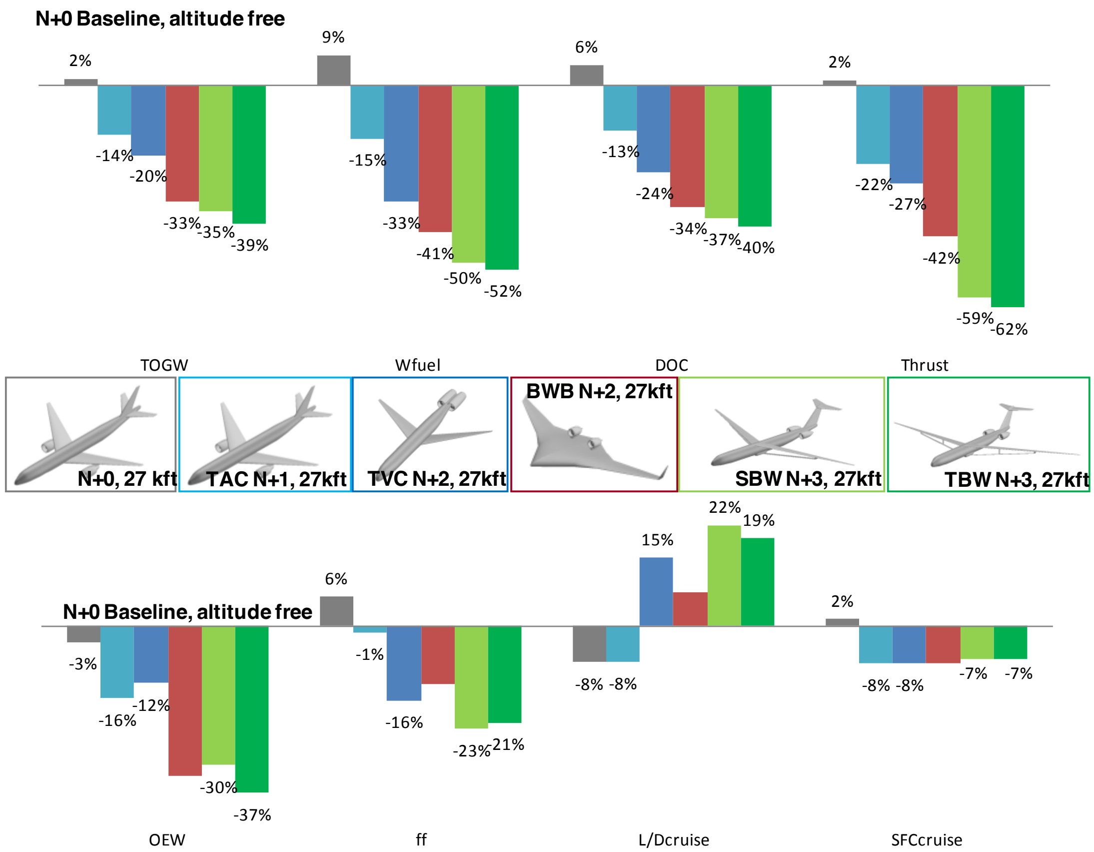

Figure 7. N+n Design Study Results - 27 kft Cruise Altitude (Reference 1)

Comparison of Design Results

When the vehicles are resized for a fixed cruise altitude at 27,000 ft

- TBW and SBW - 20% increase in fuel burn relative to the variable altitude case
- TAC, TVC, BWB - 5% percent reduction in fuel burn relative to the variable altitude case
- TBW and SBW suffer the most from cruise altitude reduction, however, still promise performance benefits over the configurations investigated
- Environmental study comparing 70% fuel burn reduction vs. 50% reduction plus cirrus cloud reduction is required before fixing the maximum cruise altitude to 27 kft
- This study demonstrates the need to explore the design mission early in the project.

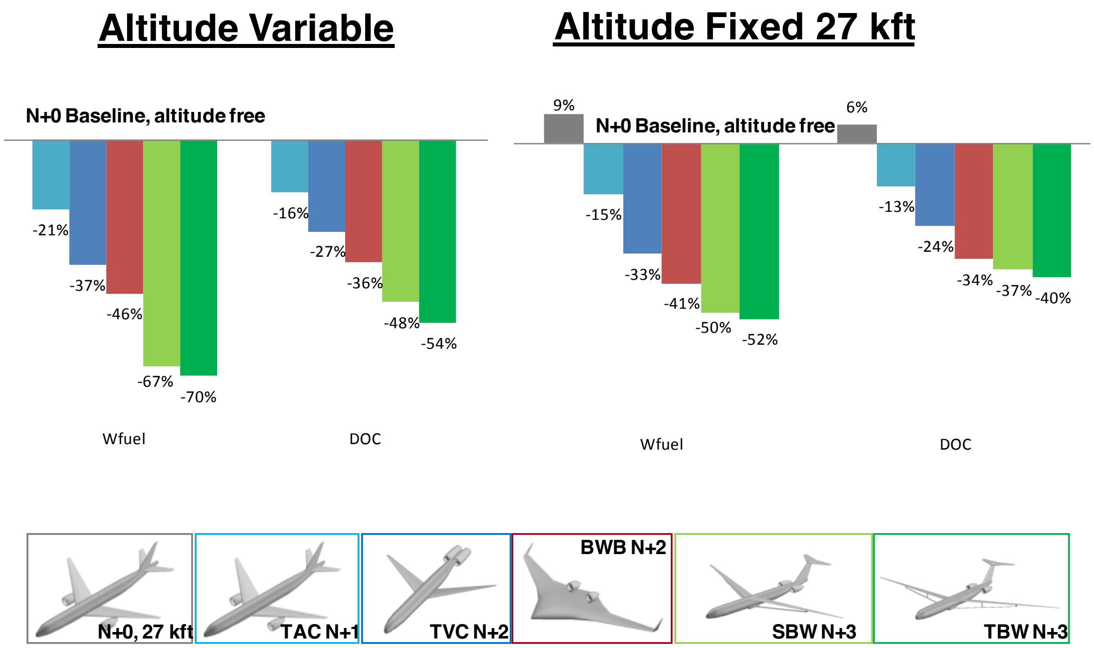

Figure 8. Comparison of Variable Altitude and 27 kft Design Study Results (Reference 1)

Summary and Conclusions

Overall, AVD^{sizing} in combination with the Methods Library has proven to be a robust and accurate tool set for transonic aircraft parametric sizing. The approach demonstrates that a single process with variable methods can be applied to conventional and unconventional transonic aircraft of extreme mission. In summary, the follow conclusions can be drawn from the case studies.

<u>Methodology Conclusions</u>

1. The total sizing methodology has proven flexibility and validity for a variety of transonic transport applications.
2. The methodology can be used to determine primary design drivers for a new engineering problem.
3. The selection of appropriate disciplinary analysis methods is critical. Incorrect methods tend to distort the conclusions, not only total accuracy but overall correctness of the solution space throughout the design process.

<u>Lessons Learned – Aircraft Conceptual Design</u>

1. TAC transports are highly sensitive to the mission due to the coupling of conflicting

disciplines and requirements despite their disintegrated appearance (distinct wing, fuselage, empennage, etc.).
2. Composite structure provides a larger benefit for long-haul wide-body aircraft s (B777) then narrow body aircraft (B737/A320) due to the effects of scale, and time spent during cruise. Long haul aircraft are more sensitive to technology improvements because of the larger fuel requirement from the mission. As such developing a next generation narrow body aircraft (B737/A320) represents a more difficult technical challenge.
3. The thrust vectored transport shows significant performance improvement over the classical TAC, if the aircraft can be proven controllable in nominal and failure conditions (ex: OEI). The current design has proven to posses significant control problems. Further design iteration is required determine if these problems can be remedied.
4. The Blended Wing Body (BWB) demonstrates a strong sensitivity to cabin aspect ratio in terms of wave-drag and structural efficiency. It is imperative to correctly perform the cabin layout within the context of the total vehicle. The classical paradigm of disintegrated fuselage and wing design no longer hold.
5. The SBW shows modest improvements in fuel savings if (1) laminar flow can be maintained as determined by the F-14 wing glove experiment, if (2) transonic interference is manageable between the strut and the wing, and if (3) the strut can reduce the total wing group weight by 20%.
6. Slowing the SBW down would allow for reducing wing sweep without a reduction of wing thickness, thus allowing increased laminar flow without a wing weight penalty due to aeroelastic constraints.

Acknowledgments

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Amit Oza
Mr. Oza currently serves as a graduate research assistant at the University of Texas at Arlington

Gary Coleman
Dr. Coleman currently serves as a Mechanical Engineer at RSG AeroDesign

Lex Gonzalez
Mr. Gonzalez currently serves as a graduate research assistant at the University of Texas at Arlington

Bernd Chudoba
Dr. Chudoba currently serves as an Assistant Professor of Aerospace Engineering at the University of Texas at Arlington

Paul Czsyz
Mr. Czysz currently serves as a consultant through Hypertech Concepts LLC