29th Congress of the International Council of the Aeronautical Sciences
St. Petersburg, Russia; September 7-12, 2014

SET-BASED DESIGN SPACE EXPLORATION ENABLED BY DYNAMIC CONSTRAINT ANALYSIS

Justin R. Kizer,* Dimitri N. Mavris*
***Aerospace Systems Design Laboratory, Georgia Institute of Technology, Atlanta, GA 30332 USA**

Keywords: *aircraft and systems integration, design space exploration, constraint analysis, set-based design, conceptual design*

Abstract

The complexity and variability of requirements make physics-based conceptual design of modern aircraft computationally expensive. To address this issue, a set-based methodology for efficient design space exploration is proposed. Enabled by a parametric, energy-based, constraint sensitivity analysis and convex hull techniques, this methodology was tested on a case study which sampled and mapped the feasible design space for a notional Large Twin Aisle passenger aircraft. Use of the methodology ultimately allowed for the identification of a robust feasible design space and within it a flexible family of solutions.

Nomenclature

P_S	specific excess power [ft/s]
T	thrust [lbs]
D	drag [lbs]
R	takeoff configuration excess drag [lbs]
V	velocity [ft/s]
W	weight [lbs]
m	mass [lbm (slugs)]
dV/dt	acceleration [ft/s^2]
SL	sea-level
g_0	acceleration due to gravity at SL [ft/s^2]
h	altitude [ft]
q	dynamic pressure [lbs/ft^2]
S_{ref}	reference wing area [ft^2]
K_1, K_2	parabolic drag polar coefficients
C_{D0}	zero-lift drag coefficient
C_L	aircraft lift coefficient
n	load factor
T_{SL}	SL static thrust [lbs]
W_{TO}	takeoff gross weight (TOGW) [lbs]
α	thrust lapse
β	weight fraction (W/W_{TO})
T_{SL}/W_{TO}	thrust to weight ratio
W_{TO}/S_{ref}	wing loading [lbs/ft^2]

1 Introduction

One of the primary objectives of the conceptual design of aircraft systems is to depict the design space and highlight possible trades for the planned vehicle [1]. In order to accomplish this task, it is paramount that the full set of system requirements be characterized and incorporated as rapidly as possible into the design process. However, complications arise due to the inherent variability of many requirements. This variability can be a product of factors such as: customer preferences, competitor actions, new regulations, volatility in fuel prices, cost overruns and schedule slippages. Combining these factors with the typical time-scale of large aircraft development programs often results in a final system that is noticeably different from what was originally envisioned [2]. Therefore, to avoid performance degradation and costly re-design, it is extremely important for any design program to maintain some degree of design freedom throughout the design process. To illustrate, one can think of navigating via a printed map with a pre-planned route contrasted with using a portable GPS. Both options can provide the nominal route to reach the destination, with the map being less costly and likely more concise than the GPS. However, with the GPS, should the driver encounter traffic on the nominal path, they possess the knowledge and freedom to intelligently re-route to a faster option. Furthermore, the map, akin to an optimized point design, is valid for a single objective function. Should the driver prefer to avoid highways or save fuel, then the pre-planned map directions may no longer provide the optimum route.

The objective of this study was to develop a methodology to efficiently provide a dynamic map for the feasible design space (FDS). Recognizing that requirements, constraints and objectives evolve over time, this map must provide a robust family of solutions that remain feasible throughout the design process. To construct this methodology, Set-Based Design (SBD) techniques were employed to map and then divide the larger design space into a series of constraint dependent feasible sets from which the FDS could be determined. To enable this exploration and mapping however, it was necessary to have an environment in which constraints and requirements could not only be rapidly evaluated, but also perturbed at will. Thus a parametric, conceptual-level physics-based, aircraft sizing and synthesis tool was developed to provide the transparency and flexibility to design a vehicle subject to varying constraints. An energy-based constraint analysis was utilized to supply the constraints and when coupled with the design tool, formed an ideal test bed for the proposed methodology. Using appropriate Design of Experiments (DOE), the design space for a Large Twin Aisle (LTA) passenger transport aircraft was explored and then the FDS discovered and mapped using adapted SBD techniques. Finally, subjecting this mapping to varying requirements and constraints allowed the identification of a robust set of possible aircraft designs.

This formulation, while applicable to a large variety of engineering design problems, is primarily motivated by the projected growth of the civil air transportation fleet and established environmental goals for the future of commercial aviation [3, 4, 5]. These objectives, which seek reductions in fuel burn, noise and combustion product emissions, will likely serve as driving requirements for the development of future civil transport aircraft. Though variable in nature and subject to developing regulations, translation of these requirements into constraints and objectives is crucial in understanding the possible shape of the design space and desirability of future aircraft systems.

2 The Feasible Design Space

Before any design decisions can be made or preferences considered, the designer must determine the set of what is possible, that is, the FDS. Knowing such information will enable trades to be performed between feasible designs and provide flexibility should a preferred design become non-optimal. To characterize and describe the FDS, a mapping is desired that will depict not simply a collection of feasible design points, but the entire feasible region as defined by all the system requirements and constraints.

2.1 Mapping the Design Space: Set-Based Design

Set-Based Design (SBD) or Set-Based Concurrent Engineering is a design methodology which presents an alternative to traditional "point based concurrent engineering" [6, 7, 8]. Instead of locking in a large number of design decisions early on in the design process to move forward with an 'optimal' point-design, the methodology seeks to simultaneously increase knowledge about the design space and relevant requirements while maintaining as much design freedom as possible [9, 10]. Traditional SBD as depicted in Fig. 1a, emphasizes mapping of the design space through the determination of feasible regions (sets) which arise from preferences in design variable values and analyses performed independently and in parallel by different disciplines [11, 12]. Because of their isolated nature and discipline driven preferences, these independently developed design spaces may be disjoint [13]. SBD then "integrates through intersection" to find a global feasible set with the objective to consider all constraints and "seek conceptual robustness" [11]. While this approach typically requires a much more resource intensive and lengthy conceptual design phase, it has been shown to mitigate costs and program delays associated with design problems encountered in detailed design or production. By carrying forward multiple design solutions further into the design process, SBD provides feasible alternatives when unforeseen problems render the nominal design infeasible or drastically degrade its performance [7].

Establishing the FDS is crucial in conceptual design, but it is entirely dependent on the requirements and constraints that determine which designs are feasible. Traditional SBD often operates on a static set of constraints, therefore, this investigation utilizes an adaptation of SBD that recognizes that these requirements and constraints can change over time. Designated as Dynamically Constrained Set-Based-Design (DynamiC-SBD), this implementation is therefore more focused on how the nominal FDS is refined through the consideration of varying constraints and intelligent re-exploration using the information contained within the individual constraint defined feasible sets. Through the connection with the sizing and synthesis tool and the energy-based constraint analysis, the different disciplines relevant in pre-conceptual design are already inherently integrated. What remains is the use of SBD principles to refine the FDS to "seek conceptual robustness" and produce a flexible family of solutions insensitive to moderate variability in constraints.

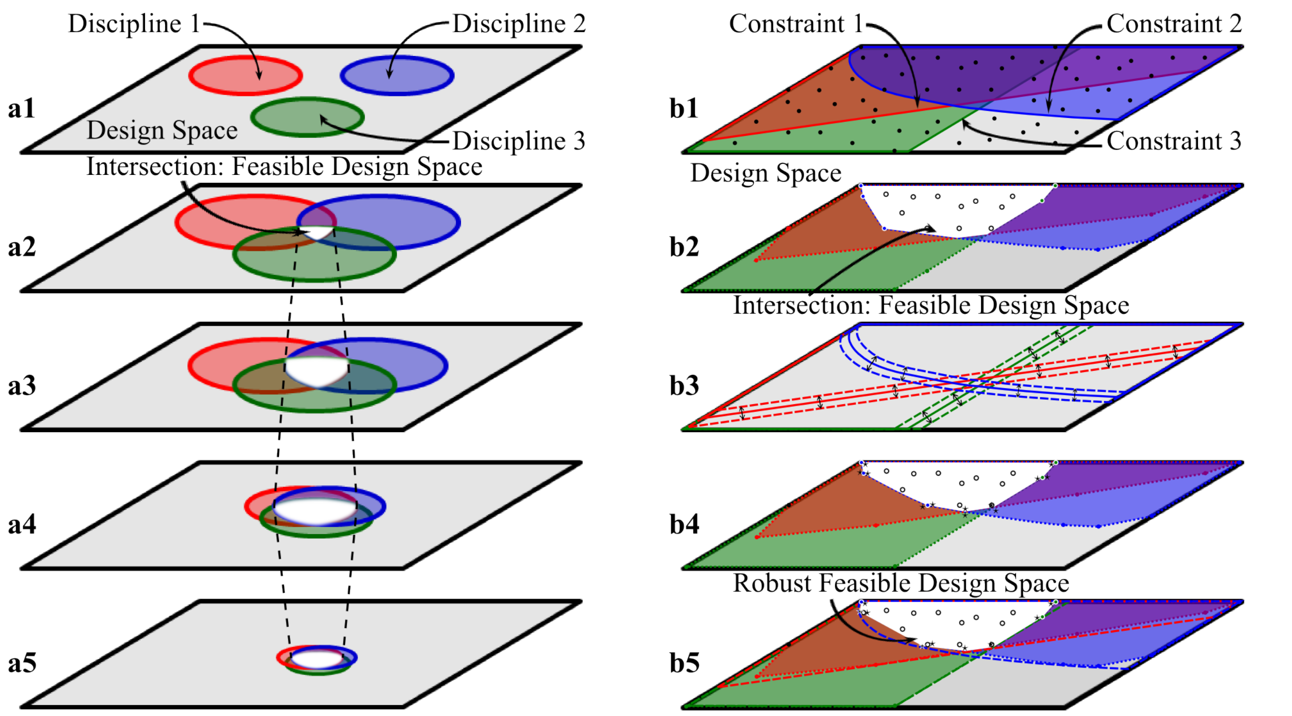
Similar to traditional SDB, DynamiC-SBD (Fig. 1b) begins with the establishment of the nominal feasible space. This is accomplished by performing an initial design space exploration with which individual constraint defined feasible sets are determined. The intersection of these constraint defined feasible sets then forms an approximation for the notional FDS. These constraints are then perturbed and the space intelligently re-sampled (targeted near areas of perturbation of active segments of the constraints). This re-sampling coupled with the initial sample set allows for the rebounding of the constraint defined feasible sets and ultimately the determination of the FDS that results from the perturbed constraints. By appropriately perturbing constraints this methodology ultimately allows for the estimation of a robust FDS.

2.2 Querying the Design Space: Physics-Based Computational Modelling

As the analysis of an aircraft system is both multidisciplinary and highly combinatorial, the determination of this feasible space is often a resource intensive task. As physical testing is infeasible at this stage of design due to the sheer number of design alternatives to be considered, physics based computational modelling is often employed. In order to explore the design space thoroughly and accommodate variable requirements and objective functions, it is desired that the computational models employed be parametric in nature. A parametric model enables rapid and semi-autonomous design space exploration, however, even with the use of such a model, there is a limit to what can be examined in search of the FDS.

2.3 Exploring the Design Space: Design of Experiments

To optimize the return of a limited experimental budget, DOE have often been employed to efficiently extract information from large combinatorial spaces [14]. Many types of DOE exist, ranging from traditional full and fractional factorial orthogonal designs to structured space filling designs to Pseudo-Monte Carlo Sampling [15, 16]. Some designs are intended to better capture behavior of the problem near the extremes of the design space, others closer to the interior. For an initial sampling and determination of the nominal feasible space, the designer should employ the DOE or combination of DOE designs which they believe to best suit the problem. However, to analyze the effects of variable requirements it is undesirable to require the re-sampling of the entire design space every time a constraint is perturbed. To avoid the unnecessary computational effort expended in retreading infeasible ground, there is a need to intelligently map the design space such that only new areas of poten-



(a) Traditional Set-Based Design

(b) Set-Based Design Adaptation

Fig. 1 Set-Based Design: Traditional Process vs. Dynamically Constrained Set-Based Design

tial feasibility need be explored. If these areas can be identified, a more targeted and efficient re-sampling of the new FDS can be performed, perhaps with a different DOE or adaptive sampling technique [17]. Furthermore, such knowledge will aid in the reinitialization of optimizers, should existing optimums become infeasible due to shifting constraints.

2.4 Evaluating Constraints: Energy-Based Constraint Analysis

The energy-based constraint analysis is a parametric physics-based formulation that is multidisciplinary in nature and useful for aircraft preconceptual design. This approach enables the gross sizing of an aircraft through the application of mission segment specific constraints expressed as functions of the two main design variables considered, thrust to weight (T_{SL}/W_{TO}) and wing loading (W_{TO}/S_{Ref}). These constraints can be derived for each mission segment/flight condition through the manipulation of a generalized energy equation (Eqn. 6) which itself arises from equating specific excess power to the time rate of change of vehicle energy (potential + kinetic) [18]. This analysis also has the advantage of requiring very limited information about the proposed aircraft. The propulsion system thrust lapse, mission segment weight fractions and a representative parabolic drag polar provide a nearly complete depiction of an aircraft to be evaluated with this analysis.

$$P_s = \frac{(T-D-R)V}{W} = \frac{d}{dt}\left(mg_0 h + \frac{1}{2}mV^2\right) \quad (1)$$

$$\frac{T}{W} = \frac{(D+R)}{W} + \frac{d}{dt}\left(h + \frac{V^2}{2g_0}\right) \quad (2)$$

$$D = qS_{Ref}(K_1(C_L^2) + K_2(C_L) + C_{D0}) \quad (3)$$

$$C_L = \frac{L}{qS_{Ref}} = \frac{nW}{qS_{Ref}} \quad (4)$$

$$\frac{T}{W} = qS_{Ref}\left[K_1\left(\frac{nW}{qS_{Ref}}\right)^2 + K_2\left(\frac{nW}{qS_{Ref}}\right) + C_{D0} + \frac{R}{qS_{Ref}}\right] + \frac{d}{dt}\left(h + \frac{V^2}{2g_0}\right) \quad (5)$$

$$\frac{T_{SL}}{W_{TO}} = \frac{\beta}{\alpha}\left[\frac{qS_{Ref}}{\beta W_{TO}}\left[K_1\left(\frac{n\beta W_{TO}}{qS_{Ref}}\right)^2 + K_2\left(\frac{n\beta W_{TO}}{qS_{Ref}}\right) + C_{D0} + \frac{R}{qS_{Ref}}\right] + \frac{d}{dt}\left(h + \frac{V^2}{2g_0}\right)\right] \quad (6)$$

2.5 Bounding the Feasible Space: Convex Hulls

Due to the nature of deterministic computational analysis tools, the design space, even if parameterized by said tools must be explored one design point at a time. To employ the principles of SBD (especially "integration through intersection"), feasible regions are sought, not simply collections of feasible points. A method is therefore needed to group these feasible points into feasible sets.

A convex hull of a collection of points can be defined as the smallest convex set which contains those points [19, 20]. If it is assumed that all individual constraint defined feasible sets are convex and continuous, then utilizing convex hulls to form boundaries around collections of feasible points defined by individual constraints will always produce subsets of the design space that conservatively approximate the corresponding feasible spaces. Under these assumptions, the set defined as the intersection of all the individual constraint defined convex hulls, is guaranteed to contain only feasible designs. This feasible set therefore approximates the FDS. This powerful result allows for the definition of the approximate FDS purely by its outermost points, i.e. the vertices of its convex hull. This implies that should an individual constraint be perturbed, to find the resulting FDS it is only necessary to determine the portion of the new FDS boundary which is defined by the corresponding convex hull for that constraint. Using this information, a targeted re-sampling can be performed near the nominal FDS boundary which was defined by the convex hull associated with the unperturbed constraint. Thus, the new FDS can be determined with confidence and efficiency, through re-exploration of only a fraction of the entire design space.

3 Proposed Methodology

Fig. 2 depicts the steps of DynamiC-SBD described herein. To form an initial estimate of the FDS for any problem, the design space must first be sampled. If little is known about the problem and a computational environment is being used to evaluate individual designs, then a Latin Hypercube Sampling (LHS) space-filling design is an reasonable choice to distribute initial samples throughout the space [21]. This design concentrates more on the interior of the design space, where computational models are more likely to be well conditioned, thus to improve the sampling of the extremes of the space this design can be supplemented with a two-level Full Factorial (FF) design which will capture the corners of the space (Fig. 2-1).

Once the aircraft has been sized, the mission segment performance can be used to evaluate each of the corresponding segment constraints for every design point specified in the DOE (Fig. 2-2). While a design will only be considered feasible if it meets all of the constraints simultaneously, it is still important to track feasibility with regard to individual constraints as this information is used to construct constraint defined feasible sets.

During this initial sampling of the design space, because the explicit functional form of a given constraint may not be known a-priori, constraints should be applied individually if possible to identify the feasible collection of designs which result from application of that particular constraint. This feasible collection of designs can then be used to construct a convex hull that bounds the feasible space associated with that constraint. Repeating this process for each constraint will ultimately yield a collection of feasible sets whose boundaries are defined by convex hulls (Fig. 2-3). The nominal FDS can then be approximated by determining the intersection of all the constraint defined feasible convex hulls (Fig. 2-4).

This nominal FDS serves as datum from which the robust FDS can be constructed (Fig. 2-N-FDS). The next step is then to perturb all constraints and then repeat the individual constraint

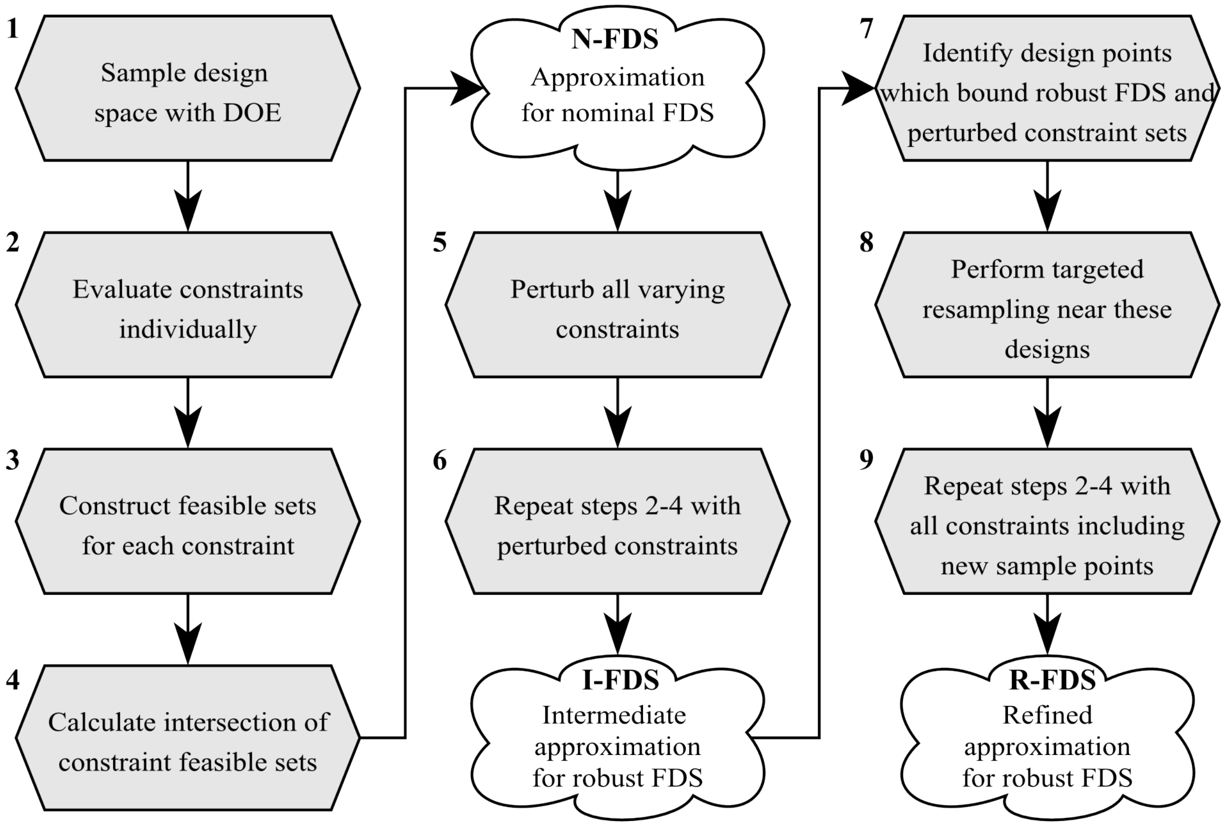


Fig. 2 Dynamically Constrained Set-Based Design Methodology Flowchart

defined feasible set construction and calculation of the resulting intersection (Fig. 2-5,6). This intersection forms an intermediate approximation for the robust design space which is constructed using only the design points from the initial sample (Fig. 2-I-FDS).

To refine this approximation for the robust FDS, regions of interest can be identified near the active segments of constraints that were perturbed. These regions can be determined by identifying design points that exist on the boundary of both the current approximation for the robust FDS and a perturbed constraint defined feasible set (Fig. 2-7). Re-sampling the design space near these points provides a refined estimate for where the new constraint boundaries now exist (Fig. 2-8). Using this information, feasible sets can be reconstructed for all the perturbed constraints (Fig. 2-9). Finally, computing the intersection of all the constraint defined feasible sets results in an approximation for a robust FDS that provides a set of solutions that will remain feasible even with moderate variations in requirements and constraints (Fig. 2-R-FDS).

4 Case Study: Design of an LTA Passenger Aircraft

As a proof of concept for the proposed methodology, a case study involving the sizing and synthesis of a notional commercial LTA passenger aircraft was selected. A physics-based parametric sizing and synthesis environment was constructed to allow for the pre-conceptual design of such an aircraft with only a few high level assumptions and little complex configuration details. While other sizing and synthesis environments were available it was decided that such a custom and high-level environment could add visibility and flexibility to the solution of the variable constraint design problem without adding unnecessary complexity.

4.1 Mission Definition and Assumptions

The LTA was sized based on a representative mission for the Boeing 777-200ER aircraft. The design range was set to 7440 nmi with a design payload of 300 passengers. The flight profile is divided into 11 primary mission segments with sub-segments defined for the climb to initial cruise altitude and descent primary segments. The flight profile is described in table 1.

Table 1 Custom LTA Mission Segments

Segment No.	Description
1.	Start and Taxi out
2.	Full Power Takeoff at SL
3.1	Accelerate to M = 0.5
3.2	Climb to 10,000 ft
3.3	Accelerate to M = 0.74
3.4	Climb to 31,000 ft
3.5	Accelerate to M = M_{Cruise}
4.	Cruise at 31,000 ft
5.	Climb to 35,000 ft
6.	Cruise at 35,000 ft
7.	Climb to 39,000 ft
8.	Cruise at 39,000 ft
9.1	Decelerate to M = 0.75
9.2	Descend to 21,000 ft
9.3	Decelerate to M = 0.5
9.4	Descend to SL
9.5	Decelerate to V = V_{Land})
10.	Land at SL
11.	Taxi in and Shut-off

4.2 Propulsion System

The propulsion system used to size the LTA was modelled using a state of the art computational propulsion simulation system. From this analysis, engine model performance was calibrated using publicly available data to produce an engine deck representative of the performance of the GE90-94B turbofan engine. Regressions for three engine power settings were then constructed from this tabular engine deck to provide expressions for thrust, ram drag and Thrust Specific Fuel Consumption (TSFC) as a function of altitude and Mach number. These regressions enabled a much more accurate prediction of the propulsion system thrust lapse for the various mission segments.

4.3 Aerodynamics

The aerodynamics used to size the LTA were derived from NASA FLight Optimization System (FLOPS) generated aerodynamics data for a baseline LTA model which provided drag coefficient values as a function of altitude, Mach number and lift coefficient [22]. This data was used to construct parabolic drag polars to establish values of K_1, K_2 and CD_0 at the appropriate flight condition for a given mission segment.

4.4 Fuel Balance

The overall sizing and Takeoff Gross Weight (W_{TO}) estimation of the LTA was determined using an iterative fuel balance approach. For each iteration, the aircraft began with estimated values for fuel weight, W_{TO} and maximum T_{SL}. The aircraft (modelled as a point mass) was then flown through each simulated mission segment in which flight conditions, forces, accelerations and mass changes were computed [23]. Once the aircraft had completed all mission segments as prescribed, the actual and required fuel weights were compared. If the discrepancy in fuel weight was not within a prescribed tolerance, new guesses for weight and thrust values were computed and the next iteration initiated. Once the weight tolerance was reached, the vehicle was determined to be converged and was then utilized to provide input for the energy-based constraint analysis. The attributes of the converged LTA are shown contrasted to a FLOPS 777-200ER baseline model in table 2.

Table 2 LTA Design Point Comparison

Parameter	Custom	FLOPS Baseline
T_{SL}/W_{TO}	0.3004	0.2966
W_{TO}/S_{Ref} [psf]	132.8	132.8
WFuel [lbs]	271,903	271,916
OEW [lbs]	320,078	320,764
TOGW [lbs]	660,623	655,891
Range [nmi]	7453	7440

5 Results

Once the vehicle sizing was complete the energy-based constraint equations were applied for each

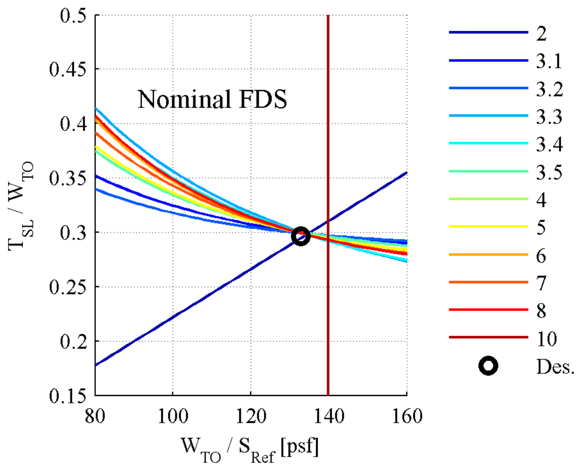


Fig. 3 LTA design space visualization through energy-based constraint analysis

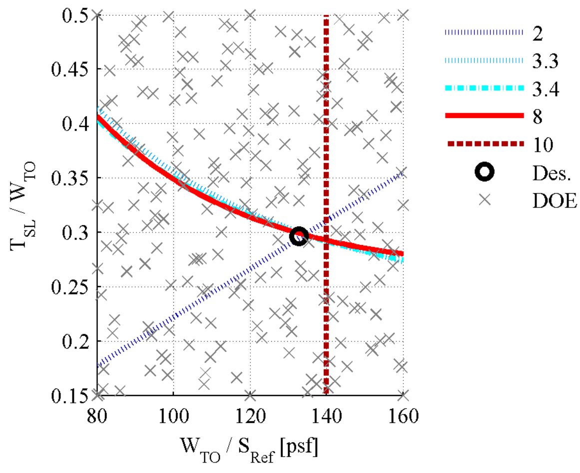


Fig. 4 LTA active constraints and initial DOE

flight condition. This allowed for a visualization of the thrust to weight vs. wing loading design space for the aircraft. It can be seen that the design point for the FLOPS vehicle to which the custom LTA was compared to lies just near the minimum feasible T_{SL}/W_{TO} as indicated by the constraint analysis (Fig. 3). It can also be seen that although many of the constraints are close together, only a small subset (approximately five of the of the twelve plotted) are active constraints which bound the nominal FDS. Finally, it is important to note is that the feasible design space is unconstrained for the larger values of T_{SL}/W_{TO} at lower W_{TO}/S_{Ref}, however for large civilian passenger transport aircraft, values of T_{SL}/W_{TO} rarely depart from the 0.25-0.4 range thus this value is artificially truncated at 0.5 to allow for ease of visualization of the relevant space.

5.1 Nominal Feasible Space

As can be seen in the Fig. 3 although the aircraft is subject to many constraints, typically only a small subset remain active. Thus for ease of visualization, the non-active constraints will now be dropped from the remaining figures (not excluded from the analysis however). Fig. 4 depicts the notional FDS defined by the five active constraints with each design of the 208 case DOE used to explore the design space depicted as an 'x' The initial DOE used consisted of 208 total designs, a superposition of a 200 case LHS and an 8 case 3-level full factorial on 2 variables (midpoint excluded). This particular design was selected to simulate not only assumed computational expense (therefore a limited budget), but also lack of knowledge about the problem and the design space. With the use of a space filling design supplemented by coverage of the edges, reasonable design space knowledge can be gained for an acceptable cost. Although perhaps not readily apparent with this example (where constraint equations are prescribed), design space exploration in such a manner is key when the functional form or governing relationships behind constraints are not known a-priori. Utilizing a DOE in this manner allows the designer to establish a rough idea of where the feasible space exists, if at all. In this effort however, the DOE serves only as the initial sampling of the space, not the final mapping.

With the space sampled, the next task was to group designs by their feasibility with regard to individual constraints. All of the designs were subjected to each constraint individually and if found feasible, placed into a set associated with that constraint (Fig. 5b). These sets were then used to construct convex hulls to bound the space defined by that particular constraint (Fig. 5c). Then, individual constraint defined convex hulls were analyzed for intersections to determine the nominal FDS. Utilizing the property that the intersection of two convex sets is a convex set [19],

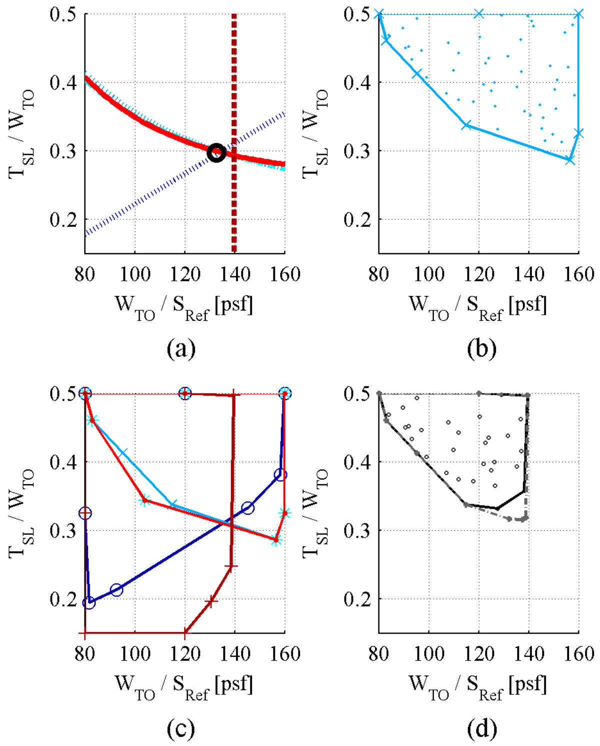


Fig. 5 Determination of the nominal FDS utilizing individual constraint defined convex hulls

an approximation for the FDS was determined (Fig. 5d). It is important to note that the FDS determined only through bounding feasible points (solid line in Fig. 5d) is a subset of the FDS determined through the intersection of the individual constraint defined convex hulls (dashed line in Fig. 5d). Through this set-based approach, information was used from nominally infeasible designs in addition to the feasible designs to determine a more accurate estimation of the FDS. Furthermore, assuming that the constraints can be evaluated individually and are always part of the vector of outputs for a design (ex. range, take-off field length, etc.), this additional information comes at no additional computational cost.

While the determination of the nominal design space is very important, the key focus of this research was to establish an efficient way for mapping the design space when it is subjected to variable constraints. The same methodology can be used for these moving requirements. With careful examination of the design space and the sets from which it was composed, the design space can be re-sampled selectively and intelligently in response to an altered constraint. To motivate this investigation, two perturbation scenarios are examined. The first is an environmentally driven scenario resulting in the perturbation of a single constraint. The second scenario features a notional perturbation of all constraints to determine a FDS robust to moderate perturbations in any of the constraints.

5.2 Fuel Burn Motivated Scenario: Horizontal Acceleration Constraint Perturbation

A new efficient aircraft engine is proposed which features drastically lowered thrust specific fuel consumption when the engine is operated near its design condition. However, due to the optimization of this engine for a specific design condition, its performance suffers notably when operating in off-design. Therefore during the mission it is desired to accelerate as quickly as possible to the design condition to minimize off-design operation. In the energy based constraint analysis formulation, this new requirement can be mapped to the modification of the required horizontal acceleration for a particular mission segment. For this example segment 3.3 was selected to be modified as it is one of active constraints defining the nominal design space. By increasing dV/dt by 20 percent for this mission segment the FDS is altered and its boundary becomes unknown. However utilizing the proposed methodology allowed for a redetermination of the approximate FDS with only minimal additional computational effort (Fig. 6b).

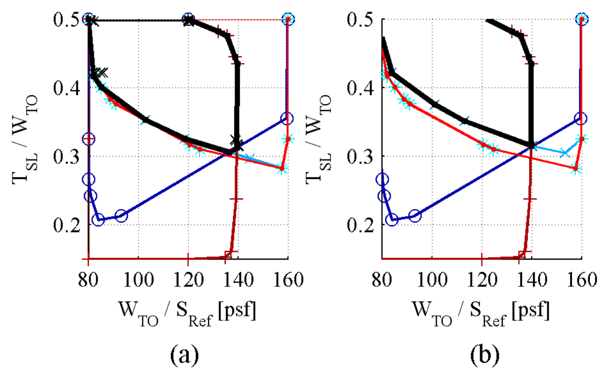


Fig. 6 Scenario: Perturbation in horizontal acceleration constraint

5.3 Finding the Robust FDS: All Constraints Perturbed

In order to determine the robust FDS all constraints must be examined and perturbed. As Requirements are rarely relaxed and when changed typically become more constraining, a notional worse case scenario was evaluated in which all constraints are perturbed in such a way to reduce the FDS. For this scenario each constraint was perturbed by 10 percent from nominal (Fig. 7c). The rest of the DynamiC-SBD methodology was then applied to determine the robust FDS containing a flexible family of solutions (Fig. 7d). This resulting FDS also highlights a region that can serve as a good fall-back point for an optimizer, as each design within this space is guaranteed to remain feasible even with relatively moderate perturbation to all constraints.

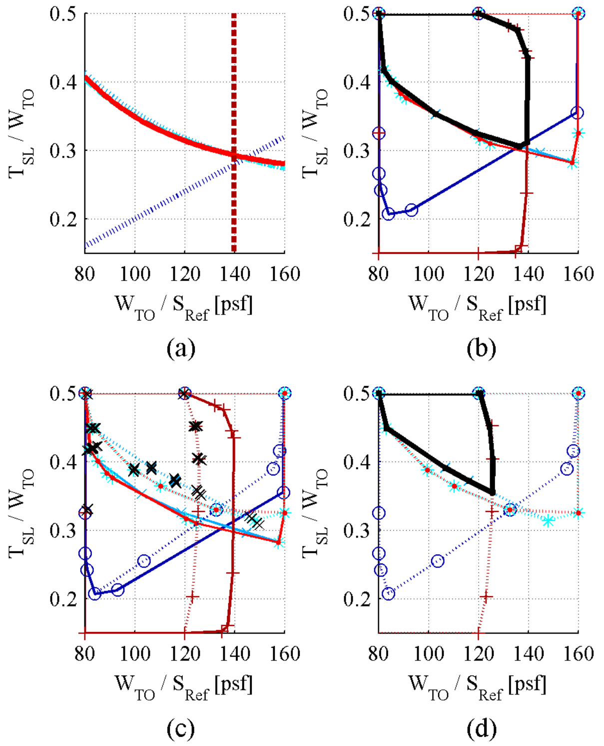


Fig. 7 FDS Robust to Perturbations in All Constraints

6 Conclusion

An adaptation to traditional Set-Based Design was presented to address the issue of determining the feasible design space (FDS) under varying requirements. This adaptation, denoted as Dynamically-Constrained Set-Based Design (DynamiC-SBD), was demonstrated through the pre-conceptual design of a Large Twin Aisle passenger aircraft enabled by a parametric, physics-based, sizing and synthesis environment and a coupled energy-based constraint analysis. A modified Latin-hypercube design of experiments was utilized to initially sample the design space and convex hulls were employed to bound feasible sets defined by each individual constraint. A notional FDS was determined through the calculation of the intersection of all the constraint defined feasible sets. Individual constraints were then perturbed and the design space re-sampled near regions of interest to rebound the constraint defined feasible sets. Ultimately this allowed for the efficient construction of a robust FDS that contained a flexible family of designs which remained feasible even with perturbation to constraints.

6.1 Future Work

Many assumptions and simplifications were made in this effort that need to be examined more thoroughly or improved upon in future investigations. The following list presents the primary improvements planned for the continuing development of DynamiC-SBD.

- Expand from 2-D to n-D design problems
- Allow for non-covex constraint spaces
- Transition from deterministic to probabilistic analysis and constraint perturbation

References

[1] Raymer D. *Aircraft Design: A Conceptual Approach*. 4th edition, American Institute of Aeronautics and Astronautics, Inc, 2006.

[2] Marsh G. Boeing's 787: trials, tribulations, and restoring the dream. *Reinforced Plastics*, pp 16-21, Iss. Nov./Dec. 2009.

[3] International Civil Aviation Organization Report HLM-ENV/09-WP/19. *High-Level Meeting on International Aviation and Climate Change* -

Agenda Item 1: Aspirational Goals and Implementation Options Montreal, Revision 1, Oct. 2009.

[4] International Civil Aviation Organization Report HLM-ENV/09-WP/1. *High-Level Meeting on International Aviation and Climate Change - Agenda Item 5: Review of Programme of Action on International Aviation and Climate Change and Recommendations to COP15.* Montreal, Revision 2, Oct. 2009.

[5] Guynn M and Berton J. Advanced Single-Aisle Transport Propulsion Design Options Revisited. *2103 Aviation Technology, Integration, and Operations Conference*, Los Angeles, CA, AIAA 2013-4330, 2013.

[6] Malak Jr R, Aughenbaugh J and Paredis C. Multi-attribute utility analysis in set-based conceptual design. *CAD Computer Aided Design*, Vol. 41, No. 3, pp 214-227, 2009.

[7] Liker J. *The Toyota Way: 14 Management Principles from the World's Greatest Manufacturer.* 1st edition, McGraw-Hill, 2004.

[8] Hopp W, and Spearman M. *Factory Physics.* 3rd edition, McGraw-Hill Irwin, 2008.

[9] Mavris D, DeLaurentis D, Bandte O and Hale M. A Stochastic Approach to Multi-disciplinary Aircraft Analysis and Design. *36th Aerospace Sciences Meeting and Exhibit*, Reno, NV, AIAA 98-0912, 1998.

[10] Ward A, Liker J, Cristiano J, and Sobek D II. The Second Toyota Paradox: How Delaying Decisions Can Make Better Cars Faster. *Sloan Management Review*, Vol. 36, No. 2, pp. 43-61, 1995.

[11] Sobek II, D, Ward A, and Liker J. Toyota's principles of set-based concurrent engineering. *Sloan Management Review*, Vol. 40, No. 2, pp 67-83, 1999.

[12] Gray A. Enhancement of Set-Based Design Practices Via Introduction of Uncertainty Through the Use of Interval Type-2 Modeling and General Type-2 Fuzzy Logic Agent Based Methods. *Ph.D. Dissertation, Naval Architecture and Marine Engineering, University of Michigan.* 2011.

[13] Stoll R. *Sets, Logic and Axiomatic Theories.* 2nd edition, W. H. Freeman and Company, 1974.

[14] Fisher R. *The Design of Experiments.* 8th edition, Oliver and Boyd, 1966.

[15] Giunta A, Wojtkiewicz S and Eldred M. Overview of Modern Design of Experiment Methods for Computational Simulations. *41st Aerospace Sciences Meeting and Exhibit*, Reno, NV, AIAA 2003-649, 2003.

[16] Cox D, and Reid N. *The Theory of Design of Experiments.* Chapman and Hall/CRC, 2000.

[17] Frits A and Mavris D. A Screening Method for Customizing Designs Around Non-Convergent Regions of Design Spaces. *9th AIAA/ISSMO Symposium on Multidisciplinary Analysis and Optimization*, Atlanta, GA, AIAA 2002-5572, 2002.

[18] Mattingly J, Heiser W and Daley D. *Aircraft Engine Design.* 1st edition, American Institute of Aeronautics and Astronautics, Inc, 1987.

[19] de Berg M, Cheong O, van Kreveld M and Overmars M. *Computational Geometry: Algorithms and Applications.* 3rd edition, Springer, 2008.

[20] Missoum S, Ramu P and Haftka R. A convex hull approach for the reliability-based design optimization of nonlinear transient dynamic problems. *Computer Methods In Applied Mechanics And Engineering*, Vol. 196, No. 29-30, pp 2895-2906, 2007.

[21] Swiler L, Slepoy R and Guinta A. Evaluation of Sampling Methods in Constructing Response Surface Approximations. *47th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, Newport, RI, AIAA 2006-1827, 2006

[22] MucCullers L. Aircraft Configuration Optimization Including Optimized Flight Profiles. *Symposium on Recent Experiences in Multidisciplinary Analysis and Optimization*, NASA CP-2327, pp 395-412, 1984.

[23] Saarlas M. *Aircraft Performance.* 1st edition, John Wiley and Sons, Inc, 2007.

7 Contact Author Email Address

Justin R. Kizer
mailto: justin.kizer@gatech.edu

Copyright Statement

The authors confirm that they, and/or their company or organization, hold copyright on all of the original material included in this paper. The authors also confirm that they have obtained permission, from the copyright holder of any third party material included in this paper, to publish it as part of their paper. The authors confirm that they give permission, or have obtained permission from the copyright holder of this paper, for the publication and distribution of this paper as part of the ICAS 2014 proceedings or as individual off-prints from the proceedings.