Tradespace Exploration and Analysis Using Mission Effectiveness in Aircraft Conceptual Design

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The success of aircraft development programs is based in requirements. Requirements are the starting point for the program and translate the key points of the operational need into what is eventually built. In many recent Air Force programs, significant cost and schedule challenges have been met. These challenges have compounded with operational requirements for improvement based on advancing and proliferating threats. The compounding issues drive a need to improve the development process. The need can be met in part by recent advancements in modeling approaches and computational frameworks. These advancements improve how operational effectiveness can be analyzed throughout design to inform the process. The work in this paper focuses on including operations analysis in the conceptual sizing and synthesis process. A modeling framework for design that can be used as a component of a decision support and requirements analysis environment is presented. The modeling framework is used in a test case of the basic conceptual design of a new tactical fighter. Results from the test case include an exploration of how changes to requirements impact the expected operational effectiveness. The critical requirements from the test case were identified and an example of a trade between critical variables was considered.

Nomenclature

S	=	wing reference area
T_{SL}	=	sea level static thrust
W_E	=	empty weight
W_P	=	payload weight
W_{TO}	=	takeoff gross weight

I. Introduction

As defense situations around the world continue to evolve, the United States Air Force (USAF) has identified two major trends that have the potential to affect its ability to complete its mission in the future. The first trend is the continuing emergence of advanced aircraft, weapons, and sensor capabilities and the continuing proliferation of threats (such as missiles, remotely piloted aircraft, and air defense systems) around the world [1]. The second trend is the continuing increases over expectations for the required cost and time to develop the systems the USAF uses [1] [2]. Recent development programs have resulted in highly sophisticated systems. However, with the current approach, the cost and time to continue to achieve the sophistication necessary for superiority is not expected to be manageable in the future [2].

The trend of increasing development cycle time for military aircraft is highlighted in Figure 1. It shows how the time from the start of a project to initial operational capability (IOC) has changed over the last half-century. Military aircraft have had a significant increase in the required time for development in comparison to the other two sets of systems. There have been similar increases in the costs for military aircraft development programs [3]. From an engineering perspective, the broad problems the Air Force sees can be refocused to look at the challenge of increasing cost and time for development. Engineering changes can have a direct effect in this focused area and potentially provide ways for future programs to avoid cost and schedule issues by improving the systems development process.

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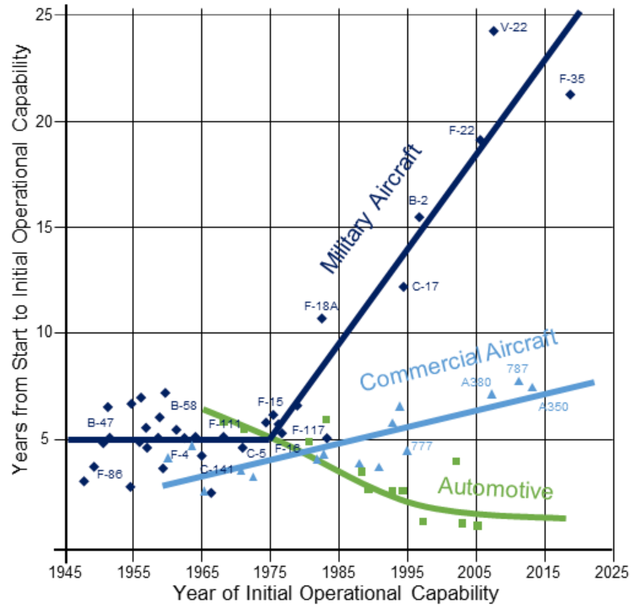

Figure 1. Comparison of time from program start to initial operational capability for military aircraft, commercial aircraft, and automotive systems. Adapted from [4].

The development process for Department of Defense (DoD) systems (and correspondingly USAF systems) broadly follows a systems engineering approach [5] [6]. In this approach, the concept exploration, concept of operations, and system requirements map directly to the actual operations and maintenance of the system. However, these two stages in the lifecycle are separated by the majority of the development program (in terms of the timeline and sequencing of the tasks involved). This separation provides a key point of interest when examining potential improvements in the process.

A review of recent research on improving the development process provides insight into what methods have the potential to do so. This research is primarily in two major areas: increased focus on the customer need and better multidisciplinary analysis. To increase focus on the customer need, some recent advances in modeling approaches and corresponding computational, analytical, and conceptual frameworks have provided new options for directly connecting a system design to expected effectiveness using operations analysis (OA) [7] [8] [9]. This is a step beyond traditional processes that involved designing a system to separately derived performance measures.

The other major effort of research into improving the development process has been in multidisciplinary analysis. New approaches seek to improve how multidisciplinary complexity is handled to improve the system design. The approaches share a common goal of simultaneously working with variables in several disciplines to bring out knowledge about the effects of strong interactions between disciplines on the overall design [10] [11] (in this paper, MDAO is used as a generalized abbreviation representing the whole set of approaches).

One major initiative encapsulating these two areas of current research is Effectiveness-Based Design (EBD). This initiative from the Air Force Research Laboratory (AFRL) has the goals of expanding the MDAO state-of-the-art, coupling conceptual design variables with OA objective functions, demonstrating the computational environment, and demonstrating the complete EBD framework [12] [13] [14] [15].

Another similar research effort is Value-Driven Design (VDD) [16]. VDD takes a more general view of "captur[ing] all the attributes important to stakeholders" and using modeling to determine an overall value metric that can be used to guide design decisions [17]. The advantage of this approach is seen in terms of simultaneous holistic evaluation of costs and benefits for systems [17].

A. Problem Formulation

Critical decisions are made during the definition and analysis of a system's requirements. In order to support decisions at that point, there is a need for an environment that allows for collaborative analysis between stakeholders. To create such an environment, connections are needed between design variables usually considered separately (such as operational effectiveness measures, system-of-systems and system architectures, multidisciplinary design variables, technology options, and capability requirements). This notional design environment uses techniques for data analytics and visualization to better communicate information that currently resides in places such as detailed technical documents, independent complex models, or the knowledge and experience of subject matter experts.

The quantitative results needed to support the notional design environment can be provided with a framework connecting discipline specific models. A modeling framework connecting discipline specific models provides a mechanism for putting the disciplinary expertise together in a way that can be queried by analytic tools. The work in this paper takes a step towards a modeling framework for design. The step involves a framework for integrating OA with traditional conceptual design. The integration of these specific disciplines is motivated by the separation between the concept exploration and requirements definition phase and the actual operational phase in the system lifecycle. The integration of OA helps to provide traceability during system design in terms of the impact of requirement changes on operational effectiveness. The discipline interaction and information exchange considered is notionally shown in Figure 2 (the focus of this work is highlighted in gold).

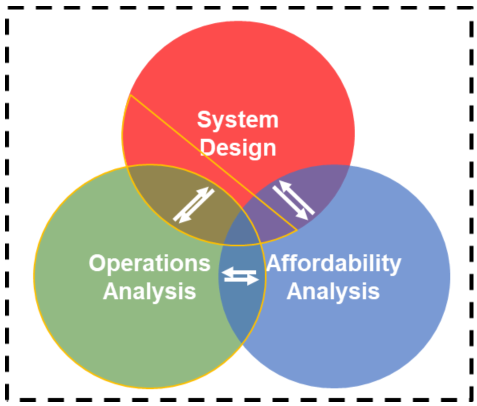

Figure 2. Connected design disciplines with the area of focus for this project highlighted in gold.

B. Background

The key element examined in this work is the improvement of early activities in the development process through a focus on the customer need. This focus uses simulation estimates of effectiveness in the operational environment to inform the requirements analysis and system design. Of note is that MDAO approaches are left as future work.

1. Operations Analysis

Factors to consider in an operational scenario include details about the entities (platforms) involved, their behavior, the operational environment, and interactions between entities. For scenarios involving military operations [18], [19], and [20] provide detailed treatments of factors that can be considered. The important factors are usually encapsulated in versions of a concept of operations (CONOPS) that describe the key conceptual factors in the scenarios and notional plans for operations [21]. The general analysis of the factors in an operation can be termed operations analysis (OA). In OA, the analysis focuses on Measures of Effectiveness (MOEs), which are the metrics of interest that define success or failure in terms of whether or not the desired ends were achieved (and the level of success or failure) [20]. OA uses either some type of modeling and simulation or else direct observations of operations to make inferences about past, current, and future operations. These inferences provide information for making decisions on potential changes to the factors and inputs involved in operations.

With the extraordinarily high costs of the real development and operation of complex systems, the starting point for OA (especially for new concepts) is based in modeling and simulation. For military systems, models and simulations used during analysis can be considered in a hierarchy in terms of the scope of an operation that they strive to represent. The scale goes from system/engineering all the way up to campaign level (shown in Figure 3 below) [22]. The aggregation can also be considered from high aggregation, low resolution at the campaign level, down to low aggregation, high resolution at the system/engineering level [22].

The research presented in this paper focuses on a scenario that is around the engagement or mission level. This is based on the goal of providing operational effectiveness insight based on a CONOPS that involves the system interacting with its environment in a system-of-systems (SoS) context. Modeling and simulation at the engagement level and above provides this SoS context.

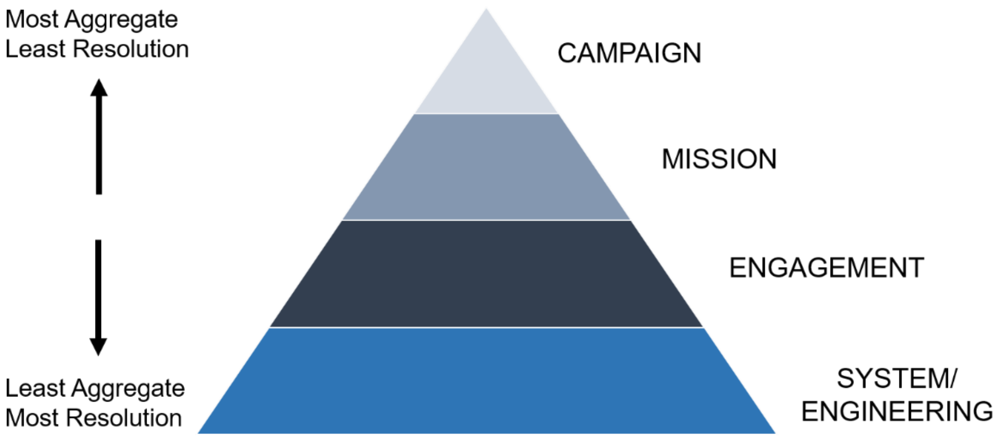

Figure 3. Hierarchy of military models and simulations. For models to be useful, as the scope increases, there is lower resolution and more aggregation. Adapted from [22].

2. Conceptual Design

The initial design process for aircraft systems is covered extensively in literature; [23] and [24] provide common academic examples. The research presented in this paper considers only initial sizing and synthesis. This portion of design involves taking a set of requirements and using constraint analysis and mission analysis to synthesize a sized aircraft design. See [25] for a detailed treatment on the variables and the derivation of the method.

Constraint analysis is an energy-based approach starting from what [25] calls the master equation. The method is used to determine the feasible design space in terms of the thrust-to-weight ratio ($\frac{T_{SL}}{W_{TO}}$) and the wing loading ($\frac{W_{TO}}{S}$). These ratios serve as the starting point in conceptual design for understanding the synthesis of the initial traditional aircraft disciplines (aerodynamics, structures, and propulsion).

Mission analysis deals with the fuel consumed for the thrust used and the estimated aerodynamics of potential designs [25] [26]. This analysis simulates a required mission similar to the one shown in Figure 4 and iteratively optimizes the weight to the minimum value required.

The system requirements are the inputs to sizing and synthesis. Converged wing area, thrust, and weights of an aircraft concept are the outputs. The conceptual design results provide a step in the translation from system requirements to the definition of the inputs needed for OA modeling and simulation. Creating a connection to expected operational effectiveness at this point in the design process provides a mechanism for informing and improving the analysis of the requirements.

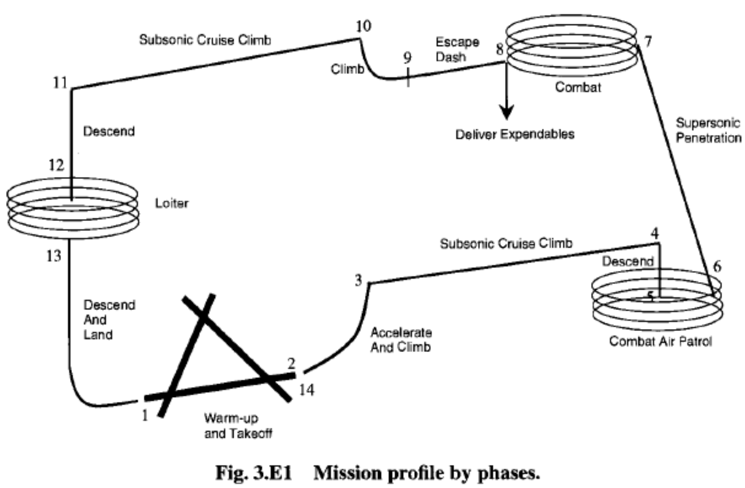

Figure 4. Example mission profile for use in mission analysis [25].

II. Technical Approach

A. Operations Analysis

The operational scenario considered herein includes a strike group of aircraft that is tasked with destroying a set of high value targets. The targets are defended by an integrated air defense system (IADS). A high-level view of this type of scenario is shown in Figure 5.

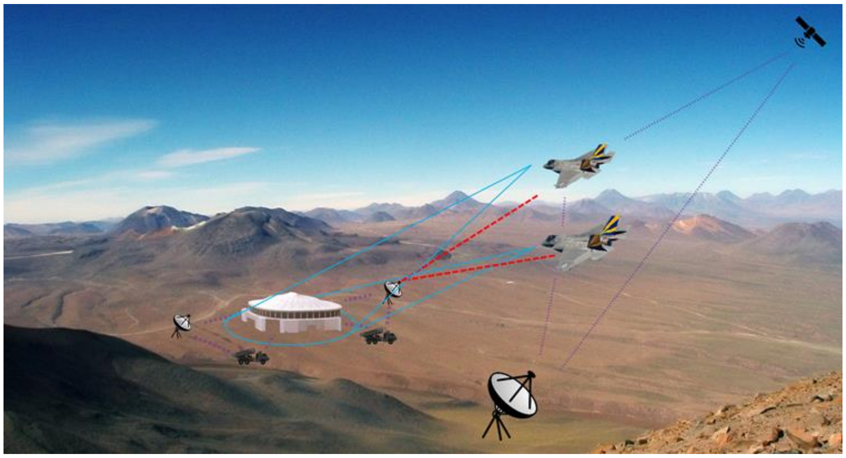

Figure 5. Operational scenario considered herein. The CONOPS involves a strike on targets defended by an integrated air defense system (IADS).

Modeling the CONOPS requires the ability to define simplified versions of the movement, sensing, and interacting behaviors of the aircraft and air defense system. An agent-based modeling (ABM) environment fits these requirements. An ABM approach models agents that have individual behaviors and attributes and can interact with each other and the environment, allowing trends to emerge [27]. Based on the options that were available, the USAF's Advanced Framework for Simulation, Integration, and Modeling (AFSIM [28]) was used due to its agent-based constructive implementation, its availability for use on the project, and its convenient options for definitions of agents relevant to the scenario of interest.

B. Conceptual Design

The portion of the conceptual design process implemented in this work was developed in Python and uses as a baseline the Advanced Air-to-air Fighter (AAF) requirements and mission presented by [25]. These define a set of performance constraints and mission segment requirements. The mission follows the profile shown in Figure 4. The requirements are given below in Table 1 and Table 2. While the requirements are defined based on a notional air-to-air mission, they have been modified slightly to account for the strike mission by changing the payload to a notional air-to-ground missile. The other requirements are assumed reasonable for a change to an air-to-ground engagement from air-to-air.

Table 1. AAF performance and payload requirements [25].

Item	Requirement
Payload	4 air-to-air missiles, 500 rounds of ammunition
Takeoff distance	1500 feet
Landing distance	1500 feet
Max Mach number	1.8M/40 kft
Supercruise	1.5M/30 kft
Acceleration	0.8M to 1.6M at 30kft in 50 seconds
Sustained g level turn	5 g's at 0.9M/30 kft and 1.6M/30 kft

Table 2. AAF mission profile requirements [25].

Phases	Segments	Conditions
1-2	Warm-up and takeoff	2000 ft PA 100°F […]
2-3	Acceleration and climb	BCM/BCA
3-4	Subsonic cruise climb	BCM/BCA
4-5	Descend	To 30 kft
5-6	Combat air patrol	30 kft 20 minutes
6-7	Supersonic penetration	1.5M 30 kft 100 nmi
7-8	Combat	30 kft 2 5g turns, 0.9M and 1.6M
8-9	Escape dash	1.5M 30kft 25 nmi
9-10	Minimum time climb	BCA/BCM
10-11	Subsonic cruise climb	BCA/BCM
11-12	Descend	BCM/BCA
12-13	Loiter	10 kft 20 minutes
13-14	Descend and land	2000 ft PA, 100°F

C. Modeling Framework for Design Exploration

The modeling framework implemented and tested in this paper includes OA and a part of conceptual design. The framework is shown in Figure 6. This combination of disciplines allows analysis of operational effectiveness during requirements analysis. The connections between OA and conceptual design are implemented through input and output files. The exploration is performed in an outer loop using Python. The starting point is the set of requirements listed above in Table 1 and Table 2. These were broadened into notional ranges for exploration of the requirements. Each set of requirements was used to size an aircraft. This resulted in values of wing area, thrust, weight, and corresponding point performance. A mapping from these values to the inputs required for OA was developed (and is discussed below). With each set of requirements mapped to a set of OA inputs (radar cross section, maximum speed, number of weapons, and maximum altitude), the OA inputs were used in the operational model to obtain values of the MOEs. The MOEs, requirements, conceptual design results, and OA inputs then provide sets of data for visualization of the design space. As shown in Figure 6, there is an option to use a loop to optimize the requirements to meet a specific objective for the MOEs. However, an optimization process was not studied or implemented in this work.

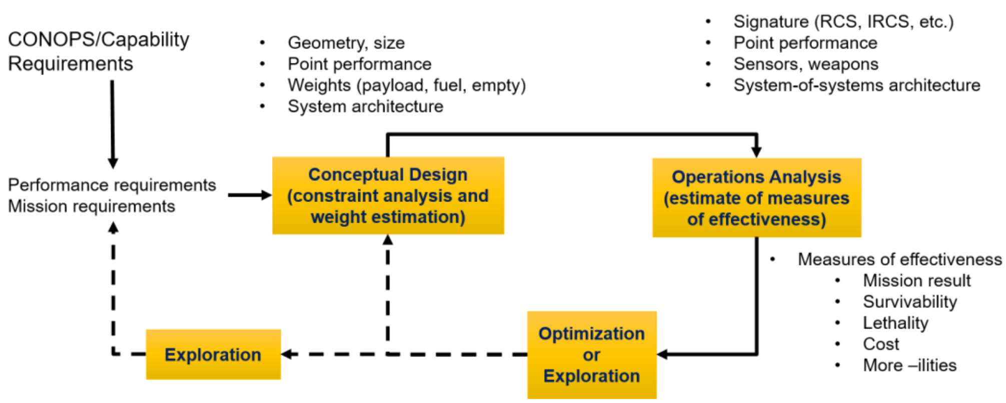

Figure 6. Overview of framework for combining OA and conceptual design in the context of requirements analysis.

III. Results and Discussion

A. Conceptual Design

A comparison of the baseline results from the sizing and synthesis code written for this project and those presented in [25] is given in Table 3. These results do show noticeable difference between this work and those presented in [25]. However, for the test case considered in this work, the results are sufficient, as the goal is to get close enough to be in the realm of reason (and to see how the results connect between the requirements, conceptual design, and OA), not to design a vehicle to a specific standard or level of confidence.

Table 3. Comparison of baseline sizing and synthesis with [25].

Baseline Results	**Reference** [25]	**Implementation**
Thrust Loading	1.25	1.1
Wing Loading	64 $\frac{lb}{ft^2}$	55 $\frac{lb}{ft^2}$
W_{TO}	24,000 lbf	24,000 lbf
T_{SL}	30,000 lbf	26,000 lbf
S	375 ft^2	436 ft^2
W_P	2,660 lbf	2660 lbf
W_E	14,650 lbf	17,600 lbf
W_F	6,690 lbf	3740 lbf

B. Operations Analysis

The baseline scenario used for OA was developed by [29]. The characteristics of the platforms (speed, altitude, sensor ranges, etc.) are based on publicly available data. The AFSIM software provided a framework for defining the communications, weapons, sensing, movement, and other functionalities that the agents use to interact with each other and their environment. The general scenario is shown in Figure 7 below. The strike group (blue side) is tasked with destroying the primary ground targets which are defended by an IADS (Figure 8). The platforms marked as having unknown locations in Figure 8 are randomly placed within an area surrounding the center of the target locations. The aircraft on the blue side have sensing and weapons capabilities on each platform, and communicate target information.

The OA inputs were the speed, altitude, radar cross section (RCS), and number of weapons carried by the aircraft on the blue side. The MOEs included the number of entities lost or destroyed, weapons used on both sides, and the mission cost for the blue side. The flight paths for blue aircraft were fixed. The behavior on the blue side was simplified to taking in sensor information, transmitting and receiving target tracks with allies, and launching weapons when targets are identified and in range. The selection of which types of elements are a part of the IADS (and how they interact) was notional. The sensor modeling on the blue side was simplified to known target locations and automatic tracking of red radar platforms that are emitting. Tests of the scenario showed that approximately 100 replications of each simulation were needed to capture the randomness in the scenario and converge to a steady state (see Figure 12 in the Appendix).

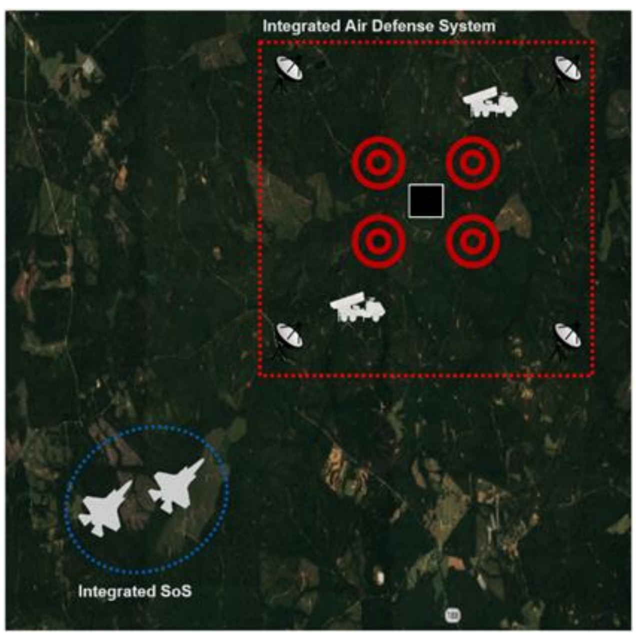

Figure 7. Overhead view of operational scenario. The blue strike group in the lower left is attacking the red targets. The targets are defended by an IADS.

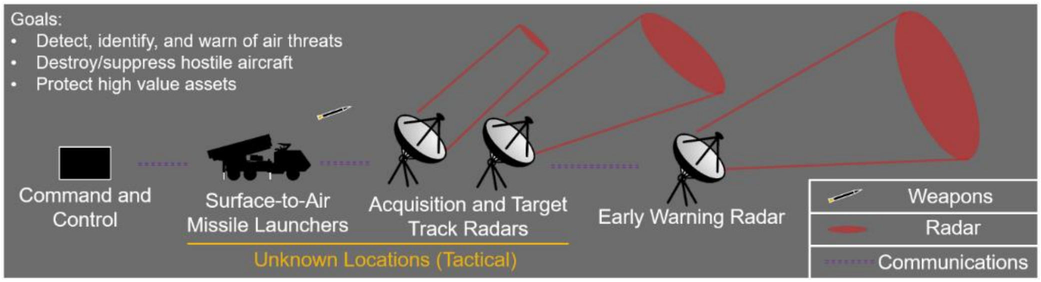

Figure 8. Components of the IADS as modeled for the operational scenario.

The number of targets destroyed is the primary metric for mission success. After destroying all of the targets, the degree of success is defined by the number of blue platforms that are lost; no blue losses is the ideal. The other MOEs inform the degree of lethality (number of red platforms destroyed), susceptibility (number of red weapons fired), and affordability through a cost estimate based on mission losses and the number of weapons used on the blue side. To make the estimates of cost, the data given in the Appendix (Table 6) were used. A notional mapping for blue platform cost was made using linear interpolation. This was based on considering a platform with the largest RCS value as having the minimum cost and a platform with the smallest RCS value as having the maximum cost.

C. Test Case of Combined Framework for Conceptual Design and Operations Analysis

In order to test the modeling framework, a test case was implemented. This test case uses the ranges of variables given in Table 4 with a JMP Fast Flexible Filling Design [30] to include points throughout the space of options. The ranges chosen were notional. Some were based on modeling limitations. The specific Design of Experiments (DOE) type was chosen based on the need to include a discrete payload weight and to sample across the interior of the space of conceptual design requirements.

Table 4. DOE ranges for requirements exploration.

Requirement	Lower Limit	Upper Limit
Supercruise Mach Number	1.4	2.6
Supercruise Altitude	10 kft	60 kft
Sustained Turn	2 g's	7 g's
Cruise Altitude	20 kft	60 kft
Combat Radius	80 nmi	300 nmi
CAP Time	5 minutes	75 minutes
Horizontal Accel Time	10 seconds	100 seconds
Takeoff Field Length	2000 ft	10000 ft
Landing Field Length	2000 ft	10000 ft
Maximum Mach (With AB)	0.5	3.0
Max Mach Altitude	10 kft	50 kft
Instantaneous Turn	5.0 g's	12.0 g's
Instantaneous Turn Altitude	20 kft	35 kft
Instantaneous Turn Mach	0.75	1.5
Payload Weight (1000 lb steps)	1500	5500

A set of 5,000 different combinations of requirements was fed into the sizing and synthesis code as inputs. The results were wing area, maximum takeoff weight, thrust-to-weight ratio, and wing loading for sized aircraft designs. From these variables a simplified mapping process was set up to convert to OA inputs. This mapping used the wing area to define the RCS based on the minimum and maximum wing areas and a notional range for RCS values from [31]. This simplified mapping provides a method for this test case, but is a key area for improvements in future work. The mapping resulted in the extension of the conceptual design DOE (and its simulation results) to an OA DOE table with ranges as given in Table 5. Each of 5,000 resultant cases were simulated in AFSIM (with 100 replications each). A mean and standard deviation was calculated for the MOEs for each case.

Table 5. Operations analysis DOE table.

Input Variable	Lower Limit	Upper Limit
Radar Cross Section	-30 dBsm	10 dBsm
Maximum Speed	287 Knots	1838 Knots
Maximum Altitude	20 kft	60 kft
Number of Weapons Carried	0 (steps of 2)	8 (steps of 2)

The approach flows design information from requirements, to inputs for conceptual design, to conceptual design results, to inputs for OA, and finally to resultant MOEs. This flow allows traceability back through the steps for analysis. The traceability can then be used to identify sensitivities and relationships between variables at all steps.

A visualization of all points across the design space is possible and a subset of this is shown in Figure 9. This shows every point in the full space available for analysis (here the number of variables is limited to fit in the format for this paper). Filtering of the inputs for points in this constellation can be used to analyze mission success. The primary driver for success was carrying four missiles per aircraft, and therefore having a minimum payload weight of 3,500 pounds. This can be seen in the third plot from the top on the right-most column in Figure 9. Once enough weapons are carried the mission is almost always successful (the plot here has not been filtered for this, but the results can be seen in the distribution of the 5,000 data points). Filtering based on survivability, i.e. on the number of blue platforms lost, the speed and RCS combinations can be constrained down to acceptable ranges for a given requirement based on percent of blue aircraft lost. The unfiltered results for survivability are shown in the top row of Figure 9. Reducing RCS and increasing Mach number both can be seen to improve survivability (with less blue platforms destroyed). Software allows real-time filtering and analysis of the constellation of points, and this visualization is one option to be potentially included in a decision support dashboard.

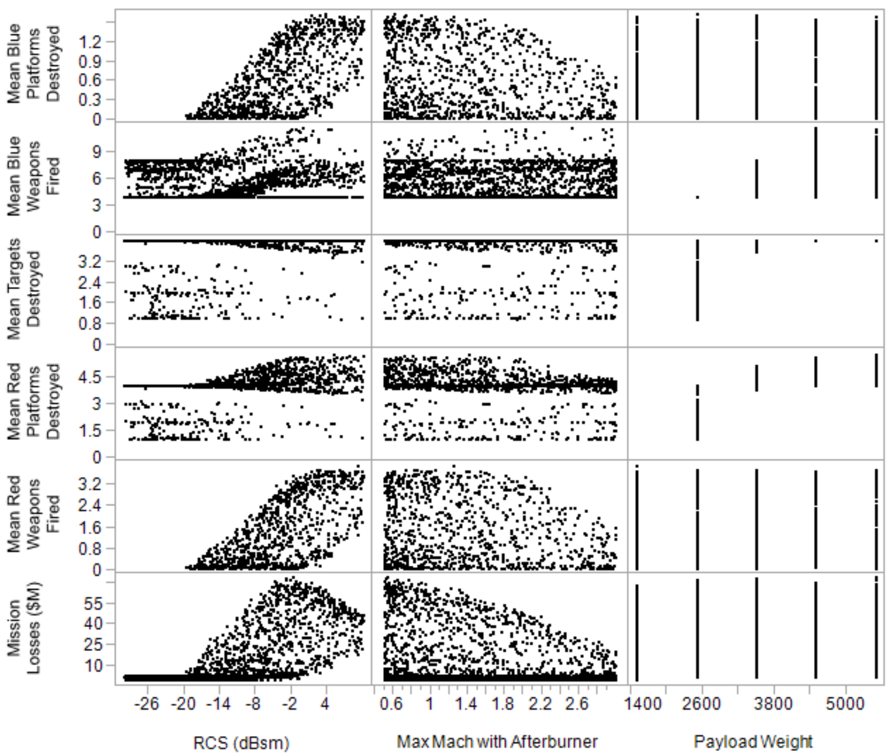

Figure 9. Selected portion of analysis space. Figure created using JMP.

1. Tradespace Analysis – Sensitivities of MOEs to Input Variables

A primary concern in analysis of changes to requirements is the effect on the variability of the MOEs. Profilers are a common visualization tool to enable this type of analysis. Each plot shows the effect on each MOE of changing each variable while all other variables are held fixed (the point indicated by the red lines and red numbers is where they are fixed). Each set of variables can be analyzed against any of the outputs that follow it in the modeling framework. One example is shown to illustrate how they can be used. In Figure 10 the sensitivity of mission losses to a set of the requirements is shown. Larger sustained g-load means larger wing area and thus larger RCS and lower survivability. For this test case critical requirements included payload weight, sustained g-load, combat air patrol time, maximum Mach number, and combat radius. The wing area was the conceptual design result with the largest impact. RCS, max speed, and number of weapons carried were all important for the OA.

One major shortcoming was the goodness of fit for the surrogate models used to enable the profilers. While connecting the OA variables to the MOEs provided a good fit, some of the other variables proved more difficult to fit. Some have quite poor fits. Two examples are the takeoff field length and the time required for the horizontal acceleration. This is suspected to be due to these requirements never being active in constraint analysis (others were more stringent). This resulted in essentially random effects on the MOEs based on the sampling of the DOE. The low fidelity of the mappings from requirements to conceptual design to operations analysis is another area potentially causing this shortcoming in goodness of fit.

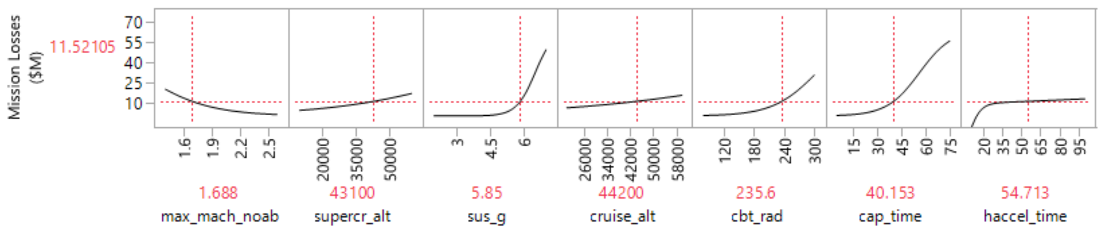

Figure 10. Example profiler of MOE responses to a set of requirements. Figure created using JMP.

2. Tradespace Analysis – Mission Effectiveness and Trade-offs

Starting with the insights gained from the sensitivities of the MOEs to the design variables, additional insight is gained through looking at tradeoffs between the key variables. In terms of effectiveness (based on destroying all targets and the cost of blue assets lost) a potential trade includes the design wing area and the requirement for maximum Mach number. This is shown in Figure 11. The horizontal axis shows design wing area and the vertical axis shows cost in terms of mission losses. The vertical axis is also broken up into five subplots, each with a portion of points corresponding to a subset of the range of Mach numbers. The data presented are filtered for only those cases where the mission was successful. The primary insight seen is that, in terms of reducing cost, the wing area has the largest single impact. The cost of the mission is near zero for small wing areas, and goes up to $50 million as the wing area increases. The maximum Mach number also has an impact on cost. Higher Mach number (lower subplots) corresponds to lower mission costs for a given wing area. The effect of wing area in this test case is due to the simplified mapping from conceptual design wing area to the RCS for OA. In terms of a trade, depending on the cost and technical feasibility of attaining a value of wing area (or more directly the RCS), the maximum Mach number provides another option that reduces mission cost.

The option for visualizations like Figure 11 provide a mechanism for trade-offs and analyses of interactions between variables. For a higher fidelity modeling framework that looks at realistic methods of determining RCS and speed, this method for visualization can provide evidence for making decisions about which areas of the design to improve, which requirements may need to be rethought, and which requirements are critical.

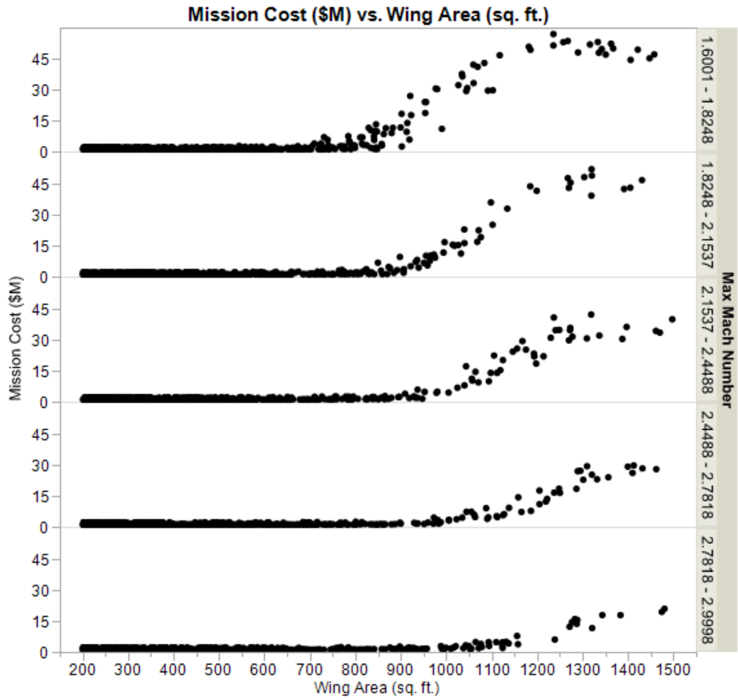

Figure 11. Trade-off between wing area, max Mach number, and cost. Figure created using JMP.

D. Future Work

Overall, the test case completed in this work offers an initial look into options for a modeling framework that connects OA with traditional design and requirements analysis. The ability to look at trades and communicate sensitivities and interactions provides a starting point and indication for what a future framework could potentially provide. Next steps need to include significant model fidelity increases, which in turn likely require MDAO methods. The mappings between conceptual design results and OA inputs would also likely drive where the fidelity increases are needed.

As an additional next step, multi-mission requirements would be more reasonable for a future program. These requirements would in turn drive a need for analysis of a set of operational scenarios instead of just one (e.g. all of air-to-ground strike, air-to-air engagement, close air support, electronic warfare, etc. instead of just one air-to-ground scenario). Lastly, while most recent high-profile development programs have been for traditional systems (e.g. strike fighters and bombers), there has also been a push for non-traditional systems that approach CONOPS in alternative ways to find order of magnitude changes in cost or effectiveness. From a conceptual design perspective, designing these types of systems involves utilizing different approaches and models than for the traditional systems. There also are multiple options for the system-of-systems architectures that put the systems together. When comparing between system-of-systems architectures and vastly different CONOPS, it is expected to become necessary to have multiple, or dynamic OA scenarios, and options for dynamic agent behaviors to make the modeling and simulation feasible.

IV. Conclusion

The leverage of requirements on the success or failure of Air Force programs provides motivation for improving the methods available for analyzing requirements. Understanding the operational need and its interactions with design requirements is critical to developing good requirements. Current research on improving the development process focuses on using operations analysis in the design process, as well as on multidisciplinary analysis. Overall, a modeling framework is needed that enables an environment for stakeholders to collaboratively explore potential design solutions. This environment ideally combines discipline impacts, expected operational effects, architectural options, and brings to light key assumptions and design trades.

This paper describes research done to develop, implement, and test an initial step for a modeling framework to connect initial design disciplines in the context of requirements analysis. The portions of design considered were operations analysis and traditional sizing and synthesis. A test case based on a strike aircraft in a relevant operational scenario was completed. The results of the test case showed the ability to use sensitivities of MOEs to requirements, conceptual design results, and OA variables to provide information on which requirements are critical. In addition, the ability to understand interactions between variables at, and between, those levels was presented. The results provide grounding for future steps towards improving the system development process.

Appendix

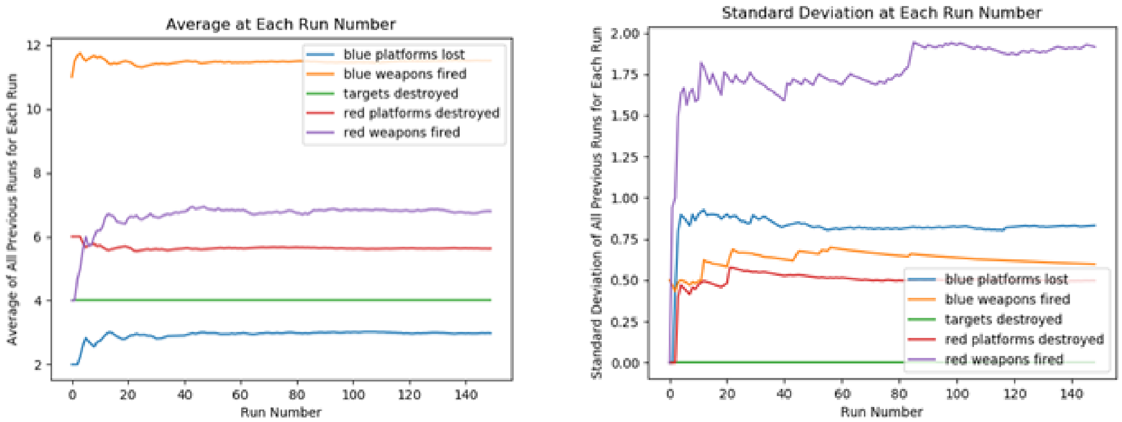

Figure 12. Test of replications needed for the first two moments on direct scenario outputs. The variation near to the chosen number of runs (100) was considered acceptable. Figure created using Matplotlib.

Table 6. Cost estimation data.

Blue Platform	**Estimated Replacement Cost (2019 $Millions)**
F-16	$29.14 [32]
F-35	$90.09 [33]
Air-to-ground missile	$0.284 [34]

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References

[1] United States Air Force, "Air Superiority 2030 Flight Plan," United States Air Force, 2016.

[2] J. Jones, "System of Systems Integration Technology and Experimentation (SoSITE)," Defense Advanced Research Projects Agency, [Online]. Available: https://www.darpa.mil/program/system-of-systems-integration-technology-and-experimentation. [Accessed 30 March 2018].

[3] Anonymous, "Defense spending in a time of austerity; The cost of weapons," *The Economist*, pp. 20-22, 28 August 2010.

[4] M. French, "Digital Systems Integration Program Committee review," AIAA, 2017.

[5] Defense Acquisition University, "ACQuipedia," Defense Acquisition University, [Online]. Available: https://www.dau.edu/acquipedia/pages/articledetails.aspx#!204. [Accessed 7 March 2019].

[6] Defense Acquisition University, "Chapter 3 Systems Engineering," in *Defense Acquisition Guidebook*, Defense Acquisition University, 2017.

[7] D. Mavris, *A "Paradigm Shift" In Complex System Design*, Atlanta: Georgia Institute of Technology, 2017.

[8] D. Mavris, "A Methodology to Create a Unified Trade-Off Environment for Advanced Aerospace Vehicle," United States Department of Defense, Hampton, 2013.

[9] P. T. Biltgen, "A Methodology for Capability-Based Technology Evaluation for Systems-of-Systems," Georgia Institute of Technology, Atlanta, 2007.

[10] T. W. Simpson, *Approaches to Multidisciplinary Design Optimization*, Penn State - Applied Research Library, 2001.

[11] J. S. Gray, K. T. Moore, T. A. Hearn and B. A. Naylor, "A Standard Platform for Testing and Comparison of MDAO Architectures," NASA, Cleveland, 2012.

[12] R. Reuter, S. Iden, R. Snyder and D. L. Allison, "An Overview of the Optimized Integrated Multidisciplinary Systems Program," in *57th AIAA/ASCE/AHS/ASC Strctures, Structural Dynamics, and Materials Conference*, San Diego, 2016.

[13] Air Force Research Laboratory, *BAA Initial Announcement w/attachments FA8650-17-S-2004*, Air Force Research Laboratory, 2017.

[14] D. L. Allison and R. Kolonay, "Expanded MDO for Effectiveness Based Design Technologies: EXPEDITE Program Introduction," in *AIAA 2018 Multidisciplinary Analysis and Optimization Conference*, Atlanta, 2018.

[15] C. Davies, "Lockheed Martin Overview of the AFRL EXPEDITE Program," in *AIAA Scitech 2019 Forum*, San Diego, 2019.

[16] P. D. Collopy and P. M. Hollingsworth, "Value-Driven Design," *AIAA Journal of Aircraft*, vol. 48, no. 3, pp. 749-759, 2011.

[17] D. Gorissen, E. Quaranta, M. Ferraro, B. Schumann, J. van Schaik, M. B. I. Gisbert, A. Keane and J. Scanlan, "Value-Based Decision Environment: Vision and Application," *Journal of Aircraft*, vol. 51, no. 5, pp. 1360-1372, 2014.

[18] United States Department of Defense, *Joint Publication 3-0 Joint Operations*, United States Government, 2017.

[19] United States Department of Defense, *Joint Publication 5-0 Joint Planning*, United States Government, 2017.

[20] United States Air Force, "Annex 3-0 - Operations and Planning," 4 November 2016. [Online]. Available: https://www.doctrine.af.mil/Doctrine-Annexes/Annex-3-0-Operations-and-Planning/. [Accessed 15 March 2019].

[21] M. Santos, *Concept of Operations (CONOPS)*, INCOSE, 2007.

[22] M. A. Gallagher, "Air Force Analytics for Decision Support," *Journal of Cyber Security and Information Systems - V3 N3: Modeling & Simulation Special Edition*, vol. 3, no. 3, pp. 4-10, 2016.

[23] J. Anderson, Aircraft performance and design, Boston: McGraw-Hill, 1999.

[24] D. Raymer, Aircraft Design: A Conceptual Approach, Reston: AIAA Education Series, 2012.

[25] J. Mattingly, W. Heiser and D. Pratt, Aircraft Engine Design, Renton: AIAA, 2002.

[26] D. Mavris, *An Energy Based Approach to Constraint Analysis - Part 2 Mission Analysis*, Atlanta: Georgia Institute of Technology, 2002.

[27] C. M. Macal and M. J. North, "Tutorial on Agent-Based Modeling and Simulation Part 2: How to Model With Agents," in *Proceddings of the 2006 Winter Simulation Conference*, Argonne, 2006.

[28] J. Zeh, B. Birkmire, P. D. Clive, J. Johnson, A. W. Krisby, J. E. Marjamaa, L. B. Miklos, M. J. Moss and S. P. Yallaly, *Advanced Framework for Simulation, Integration and Modeling (AFSIM) Version 1.8 OVERVIEW*, AFRL Technical Report, 2014.

[29] A. C. Braafladt and R. Desai, *Disaggregated System of systems Capability for Operations analysis (DISCO)*, Atlanta: Aerospace Systems Design Laboratory, 2018.

[30] SAS Institute Inc., "Fast Flexible Filling Designs," JMP, 2 Jan 2019. [Online]. Available: http://www.jmp.com/support/help/14-2/fast-flexible-filling-designs.shtml. [Accessed 4 April 2019].

[31] R. E. Ball, The Fundamentals of Aircraft Combat Survivability, Blacksburg: AIAA, 2003.

[32] Air Combat Command, "F-16 Fighting Falcon," 23 September 2015. [Online]. Available: https://www.af.mil/About-Us/Fact-Sheets/Display/Article/104505/f-16-fighting-falcon/. [Accessed 5 April 2019].

[33] F-35 Joint Program Office / Lockheed Martin, "F-35 Lightning II Program - Public Release - 2018 09 28," 28 September 2018. [Online]. Available: http://www.jsf.mil/news/docs/20180927_LRIP_11_Press_Release_v2.pdf. [Accessed 5 April 2019].

[34] "AGM-88 HARM," FAS Military Analysis Network, 23 April 2000. [Online]. Available: https://fas.org/man/dod-101/sys/smart/agm-88.htm. [Accessed 4 April 2019].