46th AIAA Aerospace Sciences Meeting and Exhibit
7 - 10 January 2008, Reno, Nevada

AIAA 2008-1443

Integrating Synthesis and Simulation for Conceptual Design

Patrick F. Cassidy* and Timothy D. Gatzke† and Charles N. Vaporean‡
The Boeing Company, St. Louis, Missouri, 63166, USA

As acquisition transitions from performance-based to capability-based, the role of conceptual design is expanding beyond platform design to include determination of mission effectiveness in a system of systems sense, evaluation of the impact of performance parameters for one or more specific missions, and assessment of the benefit of emerging technologies. At the same time, the need for improved capability is driving design toward regions of the design space where interactions between disciplines can be significant and the intuition of the designer can no longer be relied upon. This paper presents a general approach for applying multi-disciplinary analysis and optimization to address a wide range of questions related to vehicle design, system effectiveness, and required technology investment. This approach is illustrated with a design study which combines vehicle synthesis with battlefield simulation techniques to assess the impact of performance parameters on mission effectiveness.

Nomenclature

AFRL	Air Force Research Laboratory
ANOVA	Analysis of Variations
B − ACS	Boeing Aircraft Synthesis
CFD	Computational Fluid Dynamics
DOE	Design of Experiments
FEM	Finite Element Modeling
FLAMES	Flexible Analysis Modeling and Exercise System
GIT	Georgia Institute of Technology
ISR	Intelligence, surveillance, and reconnaissance
MDAO	Multi-disciplinary analysis/optimization
MOE	Measure of Effectiveness
NASA	National Aeronautics and Space Administration
NASIC	National Air and Space Intelligence Center
PIDO	Process Integration and Design Optimization
SFC	Specific Fuel Consumption
TCT	Time-Critical Targets
TOGW	Take-Off Gross Weight

I. Introduction

Aircraft conceptual design defines to a large extent what the final vehicle characteristics will be. The desired characteristics depend on the function of the vehicle. A commercial airplane will have far different

*Chief Engineer, Adv. System Concepts & Exploration, P.O. Box 516, MC S306-4245, St. Louis, MO, 63166.
†Assoc. Technical Fellow, Adv. System Concepts & Exploration, P.O. Box 516, MC S306-4245, St. Louis, MO, 63166, Senior Member.
‡Senior Engineer, Adv. System Concepts & Exploration, P.O. Box 516, MC S306-4245, St. Louis, MO, 63166.

Copyright © 2008 by The Boeing Company. Published by the American Institute of Aeronautics and Astronautics, Inc., with permission.

characteristics than a military aircraft. While designing each class of vehicle has its own challenges, a major challenge to the design of new military aircraft is determining the characteristics that ensure mission effectiveness. Because of the many design parameters that can impact effectiveness, there is a need for a flexible and efficient methodology to explore the resulting large design space.

This paper presents an aircraft synthesis methodology that has the flexibility to incorporate analysis disciplines of varying levels of fidelity and mission simulation tools into an automated analysis and optimization environment. Combining synthesis and simulation enables the mapping of technologies into capabilities. This is demonstrated for synthesized vehicles performing a specific mission. The result is a process for identifying the key performance parameters that determine mission effectiveness.

The Boeing analysis and optimization environment is based on commercial software, such as ModelCenter[1] by Phoenix Integration or iSIGHT[2] by Engineous Software. The primary platform synthesis tool, Boeing ACS (B-ACS),[3] is a successor to the NASA ACSYNT code which has been customized for Boeing by a third-party vendor, AVID. B-ACS supports various levels of physics for aerodynamics, propulsion, mass properties, and cost analyses. The simulation code integrated for this study is the Flexible Analysis Modeling and Exercise System (FLAMES)[4] developed by Ternion. The integration of these tools creates a flexible multi-disciplinary analysis and optimization (MDAO) environment, which permits alternate or customized components such as radar sensing models, cost models, and structures models to plug in as needed.

I.A. Background

The process of design really involves asking and answering a series of questions that become more detail oriented as the design progresses. These questions lead to notional requirements, which in turn drive the configuration features and technologies.[5] At the conceptual level questions might include "What is the mission?", "What class of vehicle should be designed?", or "How big should it be and how much will it cost?". Detailed design questions might include "What is the detailed shape?", or "Can drag be reduced and range increased?". The key is asking the right questions and answering them with analysis results.

Traditional tools and processes support designing vehicles for specified performance or a specific mission. But due to geopolitical changes, the mission may not be known in advance. So in what technology capabilities should investment be made given geopolitical concerns[6]? What assets need to be on hand when an event occurs? It is necessary to be able to respond to challenges posed by newly emerging threats and operational scenarios, such as terrorism, counter-terrorism, homeland-defense, and urban warfare. It takes too much lead time to design and build a vehicle once a threat is known. Rather than "Given performance criteria, what vehicle can satisfy the criteria?", one of the key questions becomes "Given a set of possible missions, what should the performance criteria be?".

An historical approach to design was to draw up a vehicle concept and then have different subject matter experts apply their domain knowledge to analyze the configuration and assess its strengths and weaknesses. Design space coverage was based on how many designs the designers and analysts could produce. The primary drawback of this manual process is the limited coverage of design space. Small integrated design teams were formed to accelerate the process, but a lot of expertise was still required to make sure configurations were in the right ballpark.

Two technological advances are having significant impact on design processes; computational analysis and optimization techniques. As the complexity of vehicles and their flight regimes have expanded, rules of thumb and empirical methods are giving way to computational techniques. Over a decade ago, Rubbert[7] outlined the shift in commercial aircraft design from technology driven to market driven, and how technologies such as computational fluid dynamics (CFD) best add value to the design process. While much of the effort has been focused on computationally intensive applications like CFD and structural finite element modeling (FEM), the increase in computational resources also enables faster analysis techniques to be applied to much larger design spaces. Large scale analysis and optimization techniques enable rapid modeling and sorting through the design space. In essence, the design analysis methods are not new, just faster and more thorough. But this still represents a change in the design processes consistent with Rubbert's paradigm.

Another key benefit of computational analysis and optimization is the ability to link different disciplines together. Past siloing prevented direct interaction between disciplines. Linkage helps avoid adverse interactions between technologies and greatly enhances the opportunity to take advantage of synergies. Zink et al.[8] developed a multi-disciplinary optimization methodology that included refinement of fidelity of the analysis models and applied it to the high speed civil transport design problem.

Cost is another example of a discipline that can be incorporated into this environment. In the past, minimizing hardware acquisition costs was not a significant driver in selection of air-vehicle weapon systems. Numerous air-vehicles have been produced, with emphasis on meeting performance objectives given by the customer, with cost being a secondary consideration or afterthought. But cost has become a major driver in today's acquisition process. Cost estimation can vary from a simple estimate of cost based on the weight of the overall vehicle and subsystems to a detailed cost model. For example, Anderson et al.[9] have investigated life-cycle cost reduction in inlet design.

Quite a bit of optimization has been applied to detailed aircraft design, where the longer design cycle time is compatible with more numerous and higher fidelity analysis runs. Structural optimization and more recently aerodynamic optimization using CFD are the most common. Gatzke et al.[10] applied Navier-Stokes CFD analyses to a sensor fairing design problem, and many other narrowly focused applications have been reported. As computer power increases, more emphasis is being placed on moving these types of analyses and optimizations earlier in the design process. Approaches have used statistical methods[11] or models that capture uncertainty[12] to simplify the system to be optimized. While this is an important consideration, this paper highlights benefits of being able to rapidly analyze/optimize vehicle configurations by bringing in more analysis disciplines at reasonable levels of fidelity.

II. Process Integration and Design Optimization Environment

A Process Integration and Design Optimization (PIDO) software environment automates processes through tool integration employing input and output file parsing or wrapper technology. Once the synthesis code and other modules are integrated, the PIDO environment repeatedly exercises each individual software component for each variation of the input variables to automatically, systematically, and rapidly explore the design space. The output of the PIDO integrator is the Design of Experiments (DOE) data set or optimization results. The results are queried to find the most capable of those candidate configurations, which can be selected for further detailed configuration synthesis refinement.

This flexible Boeing design process is also able to incorporate additional technologies as well as additional vehicle requirements (such as supersonic performance). The process can be readily tailored to optimize desired customer improvements in particular areas in terms of performance, cost, or technology availability. The technology models calculate the modifications to the aircraft synthesis code inputs that are required to represent the incorporation of that technology into the configuration.

Engineous Software's iSIGHT[2,13] and Phoenix Integration's ModelCenter[1] are two such software integration environments. These environments manage the input and output parameters to the analysis codes, linking the output of one code to the input of the next. Boeing ACS has been integrated with both environments. Once integrated, either environment can set up, monitor, and analyze from hundreds to thousands of design runs generated by Boeing ACS.

II.A. Design of Experiments

Design of Experiments is a systematic set of analysis runs that generate data relating analysis outcomes to the input parameters. This data is used to represent and analyze the behavior of the system. Based on varying a selected number of design parameters, such as payload, mission, and geometry parameters, the pertinent parameters, and value ranges for the various DOEs will be defined. Pareto studies can be conducted in order to identify and isolate the input parameters that have the most significant contributions to overall utility in terms of effectiveness and affordability. The Full-Factorial DOE analytical method is the "brute force" method and results in high-density, high-fidelity design spaces where parameter interactions can be readily identified. The large number of input parameters can present challenges in terms of the computational power required and the processing time. In consideration of these challenges, orthogonal or sparse matrix methods, such as Latin Hypercubes, may be used, along with smaller DOEs representing portions of larger DOEs. As results are scrutinized, further refinements can be made to increase model fidelity in subsequent iterations.

Candidate aircraft configurations can be evaluated using figures of merit to identify regions that are relatively close to a local optimum. Subsequent refinement steps apply the Air Vehicle Synthesis Methodology, possibly with higher fidelity analyses, to further optimize the preferred configurations.

Individual cases may diverge and result in a non-convergent solution, which is tagged by the PIDO environment as an infeasible design run. Areas within the design space where there are no convergent solutions are considered infeasible design spaces. The automation of design space exploration is particularly beneficial to find the feasible region in these cases.

II.B. Analysis tools

II.B.1. Boeing-ACS

Boeing ACS (AirCraft Synthesis)[3] is the Boeing 'Level 0' air vehicle configuration synthesis tool. It is an enhanced and upgraded version of NASA's ACSYNT code, a FORTRAN computer program that was developed in the early 1970s by the NASA Ames Research Center. Boeing ACS is an interdisciplinary aircraft synthesis program that is comprised of the following modules: geometry, trajectory, aerodynamics, propulsion, and weights. The geometry parameters, such as wing area, aspect ratio, fuselage length, etc., define the aircraft dimensions and shape. The trajectory module simulates a basic user-defined mission, for example, take off, climb, cruise, loiter, cruise, descent, landing. The trajectory module calls upon the aerodynamics and propulsion modules to determine performance at each mission point based on parameters such as airfoil shape, drag components, engine thrust, and specific fuel consumption. The combination of the estimated gross weight, lift-to-drag, thrust, and specific fuel consumption (SFC) characteristics determines the fuel burned at each mission point. Other important data, such as sustained and instantaneous turn rates are available in the detailed trajectory output in the output file.

II.B.2. FLAMES

FLAMES[4] is a commercially available, general simulation framework, which can model the behavior of many different types of systems. A collection of software services provides the basic building blocks for all FLAMES-based applications. Developing a FLAMES-based application involves developing models that simulate specific systems and plugging them into the FLAMES standard applications. This ability to customize FLAMES is used to incorporate vehicles synthesized with Boeing ACS. Models include both equipment models, which represent the functionality and interaction of physical devices, and cognitive models, which capture human decision processes and manage information and communication between units. This capability supports simulation of complex battlefield scenarios.

II.C. Design Space Exploration

Metrics objectively, quantitatively, and numerically characterize the relative performance of a given configuration. These metrics always trace back to fundamental questions of performance capability: "How fast?", "How far?", "How high?", "How maneuverable?" or, in the case of affordability, "How much does it cost?" or "How much does it cost to operate?" Metrics, defined as a function of various system parameters, are calculated for each analysis performed.

The values for a predefined set of parameters are varied for each analysis run, while most other parameters are held constant. Some subset of parameters may be used to 'size' the vehicle in an attempt to meet mission requirements. For example, with fixed wing area and engine parameters, the fuel weight may be varied to meet a specified range requirement. An iterative scheme is applied in order to address the interdependencies between parameters, such as fuel weight and take-off gross weight (TOGW), and drive to a convergent solution.

II.D. Applications

Boeing's Air Vehicle Synthesis Methodology can be applied to a range of conceptual design studies including assessing sensors, structures, aerodynamics, communications, guidance, weapons systems, propulsion and power, mission computers, flight controls, and control station technologies, technologies for detecting, tracking, and engaging Time Critical Targets (TCTs) (an important capability in recent conflicts), and Swing-Wing, Oblique-Wing, and Morphing-Wing technology relative to Fixed-Wing configurations.

The methodology can be used to identify the importance of properties such as range, endurance, high-subsonic dash capability on mission effectiveness. The next section will address a specific design study aimed at finding the key performance parameters.

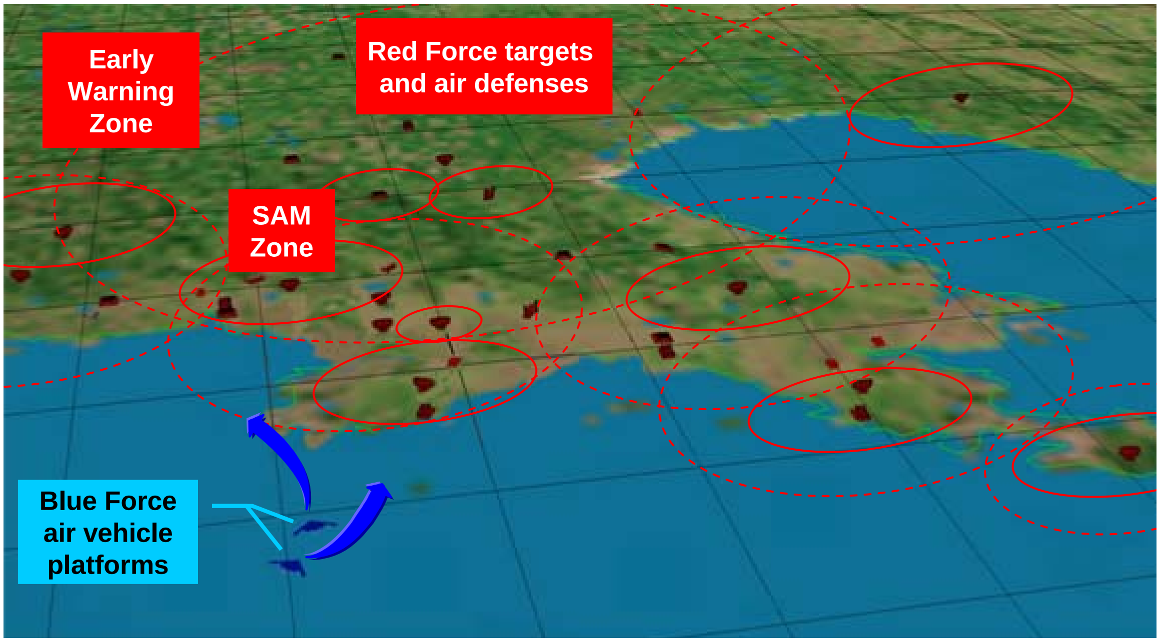

Figure 1. Sample Mission Scenario. Red targets include radar and surface-to-air missile defenses, transporter-erector launchers, theater ballistic missiles and cruise missiles, and command centers. Targets may be assigned different priorities based on their accessibility and threat. Certain targets, such as the transporter-erector launcher, are considered time-critical due to their mobility. The blue force consists of one or more platforms, which can employ a variety of weapons loadouts.

III. Design Study

III.A. Objective

This study focuses on determining key performance parameters for an air vehicle operating as part of a Strike Force. The mission of the Strike Force is to clear the way for other air assets. A useful aspect of the simulation framework is that it allows the enumeration of a 'threat level' for each target. The mission is considered successful when targets with a threat level above a given threshold have been neutralized.

Underlying research questions involve the impact of basing constraints, minimization of take-off gross weight, advantages of advanced engine technologies, relations between size, performance, and payload weight, and the relative merits of speed, range, and persistence of weapons compared to speed, range, and persistence of the vehicle. The answers to these questions are a function of the mission scenario.

III.B. Mission

In order to demonstrate the combined synthesis and simulation process, a sample mission scenario was selected. The mission scenario is focused on a peninsula accessible by water routes. The scenario is unclassified, and is created by specifying locations for various assets on a terrain map. An example force layout is shown in Figure 1. Representative basing distances from the target area in the range of 1000-3000 nm were evaluated.

Hostile (Red) forces consist of ground-based air defense systems, airbases, time critical targets such as transporter-erector launchers and theater ballistic missiles, and other targets of interest. Air defense systems were modeled using NASIC HELIOS Unclassified models. No air-to-air defenses were modeled. The objectives of the red forces are to defend the hostile region against the blue forces and to use mobile short range ballistic missiles to fire upon the nearest allied territory. Red forces will use generic unclassified surface-to-air missile site models. The radar power of these sites is variable as a first order method to represent improvement or degradation in performance.

Allied (Blue) air forces consist of parametric manned subsonic vehicles with parametric munitions, and unmanned aerial sensorcraft. The vehicle can be parametrically varied to represent the properties of a current asset. Two regions of the design space of primary interest are long range vehicle/short range weapon and

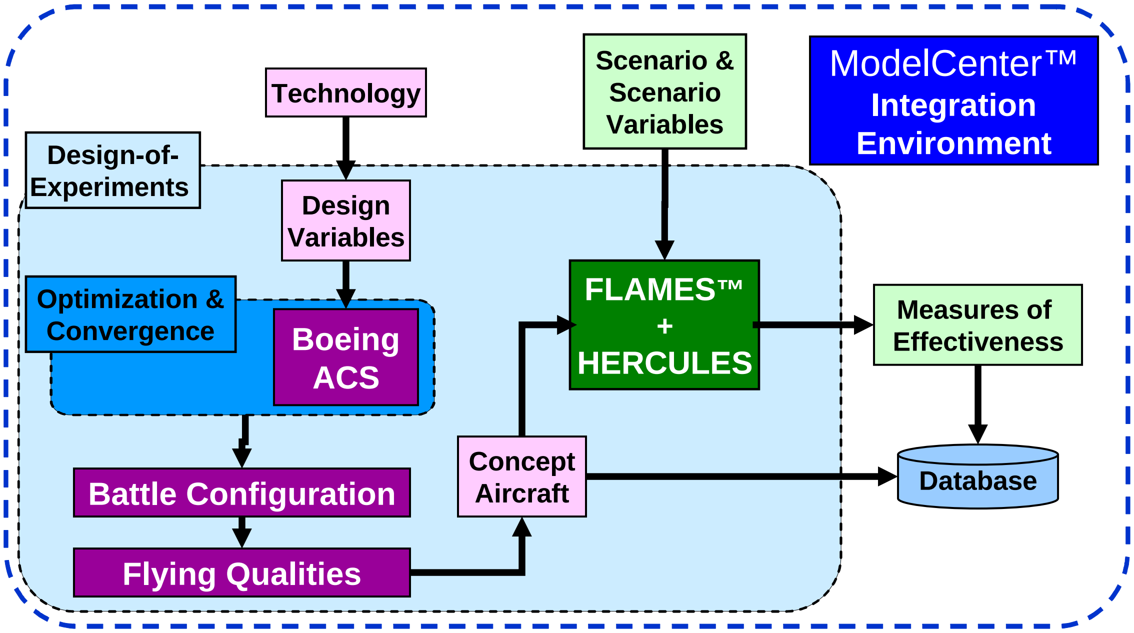

Figure 2. Boeing Aircraft Synthesis Environment. The aircraft analysis and simulation tools linked by the integration environment provide flexibility for controlling the fidelity of analysis methods and vehicle and cognitive models.

short range vehicle/long range weapon. Blue ISR will detect and identify stationary and moving targets. The weapons will attack both stationary and moving targets. The target engagement priority is from highest to lowest. Up to six, identical, identically armed, subsonic vehicles may be modeled in the scenario. Perfect communication and perfect sensing are assumed.

III.C. Analysis Process

In order to determine key performance parameters, this study defined several Measures Of Effectiveness (MOEs) for the mission, and systematically evaluated them using the Boeing Aircraft Synthesis Methodology. Phoenix Integration's Model Center was utilized as the PIDO executive for running DOEs and optimizations within this process. Boeing ACS was used as the aircraft synthesis tool and mission simulation was accomplished by applying FLAMES to a realistic scenarios. Based on results from the initial phase of the study, the FLAMES move model for the platform was subsequently upgraded with the Herc6DOF class six degree of freedom move method. The process is shown in Figure 2.

An Engine Technology Factor was input into Boeing ACS to capture the effect of engine technologies such as variable cycle engines. This effectively adjusts the SFC of the engine. A Vulnerability Factor was input into the FLAMES platform characteristics to account for technologies such as electronic jamming or decoys. The Effectiveness Factor was a FLAMES munitions input that takes into account the vulnerability of the munition and the probability of successfully hitting and killing the target. The munition, sensor, and data processor models used in this study were developed at Georgia Institute of Technology (GIT).

Blue forces also made use of the GIT Intelligent Battle Manager[14] cognition models for air tasking. These models were "trained", using a series of analysis runs for a single platform, to support engagements using several aircraft and munitions combinations.

A preliminary step in the process was to run an Analysis of Variation (ANOVA) study to determine the sensitivities of the candidate parameters on MOEs. Based on this, a reduced set of parameters was used in subsequent DOE studies to determine candidate solutions.

The executive varied the target Takeoff Gross Weight (TOGW), Wing Sweep, Wing Taper, Wing Aspect Ratio, Wing Loading, Wing Root Thickness to Chord Ratio, and Thrust to Weight Ratio. For a specific run, setting the Wing Loading sets the Wing Area. The Wing Tip Thickness to Chord is set as a function of the Wing Root Thickness to Chord. The Fuselage Body Length scales with the TOGW. Then with a specified

Table 1. Candidate Measures of Effectiveness

Function	*Measure of Effectiveness*
Survivability	Number of Blue Assets Survived
	Number of Blue Assets Killed / Survived
Lethality	Number of Red Targets Killed
	Number of Red Targets Killed / Number of Blue Targets Lost
	Number of Red Targets Killed / Munitions Fired
	Number of Red Targets Killed / Time of War
Persistence	Time of War
	Number of Sorties
	Rate of Red Transporter-erector Launchers Killed
	Number of Red Theater Ballistic Missiles Launched
	Number of Red Transporter-erector Launchers Killed

Fuselage Fineness Ratio, the Fuselage Maximum Width is set. In the DOE, munition weight (payload weight) will vary based on number of munitions and bomb weight. The final TOGW was calculated within B-ACS based on input payload weight, wing area, range and target TOGW. In the weight calculations within B-ACS, the fuel weight was an output parameter. A set TOGW and Thrust to Weight Ratio determines the Engine Thrust. Internal engine sizing within B-ACS for a target Engine Thrust determined the SFC.

Candidate MOEs are given in Table 1. The MOEs were chosen to address the research questions posed for this study. These questions included:

- What are the vehicle size and performance sensitivities to payload weight and size requirements?
- What are the impacts of geographical and geopolitical basing constraints on fleet size, sortie rates, weapons loadout?
- What are advantages of advanced engine technologies for both weapon and vehicle performance?
- What is the minimum TOGW required to have sufficient persistence and weapons carriage to accomplish a variety of missions?
- What impact do multi-weapon loadouts have on survivability and lethality?
- What weapons and payloads are required to prosecute various missions?
- How do weapon type and availability affect the dash capability requirements.?
- What are the relative merits of speed, range, and persistence of weapons compared to speed, range, and persistence of the vehicle?

Analyses of MOEs as a function of parametric inputs were used to determine optimization of: 1) aircraft survivability, 2) effective payload, and 3) persistence at selected targets. In addition, the MOE analyses were used to study: 1) relative benefit of weapon vs. platform speed, 2) probability of target detection, 3) probability of target kill, and 4) effect of basing.

III.D. Results

Several observations can be gleaned from the initial DOE results. For this pilot scenario modeling hostile forces with formidable defenses, the primary driver for mission effectiveness was the range of the weapon. With a suitably long range missile, the aircraft is able to stay out of range of the enemy air defenses. Employing the lightest munitions able to meet this range requirement increases the number of munitions, thereby reducing the number of sorties required. The most important vehicle parameter was the ability to avoid detection. Otherwise, the missile range dominates. Another factor affecting Blue vehicle losses was vehicle range, which accounted for losses in the DOE due to fuel depletion.

The results of this study agreed with expected outcomes for such a challenging scenario, and provided proof-of-concept validation for the combined synthesis and simulation environment. This was the first phase of a spiral development activity. Spiral two is looking at variations of the scenario to determine how the importance of parameters depends on the details of the scenario.

III.D.1. Model Refinement

The initial scenario was constructed with known issues related to idealism in the modeling and limited weapons capabilities. For example, some of the built-in FLAMES capability represents placeholders to be replaced by the user's application specific models, and therefore are not intended to capture accurate physical effects. Evaluations in the 3D visualization environment showed that while the built-in movement models were reasonable for simple movement, they produced unrealistic turning rates and angle of attack conditions for more complex maneuvers. This was the impetus for incorporation of the Herc6DOF class six degree of freedom move method. This more accurate move method was particularly important for representing air-to-air combat or for avoiding surface-to-air missiles.

The scope of the analysis was expanded by adding additional munitions model options. A generic model was developed that could parametrically vary range, speed, size, accuracy, cost, and probability of kill. This enabled modeling munitions ranging from gravity bombs to hypersonic missiles.

As demonstrated in this study, analysis can be performed with a mixture of physics-based and effects-based models. In this example, aerodynamics, propulsion, and weights properties are physics-based, deriving from an analysis of a vehicle. Characteristics such as kill probability and missile accuracy are effects-based, i.e., derived without a detailed modeling of the flight and impact of the missile. The flexibility of this analysis methodology allows rapid incorporation of new models. Analysis using the refined model is in progress.

III.D.2. Summary

Review of the results from the initial phase of this study can be understood in the context of the assumptions and simplifications built into the models used. This illustrates the importance of careful determination of how much fidelity is required and selection of models. For example, the higher fidelity move methods incur a significant overhead that is acceptable for complex maneuvers where they are critical, but the simpler move method is preferred for basic operation.

This numerical experiment demonstrated the effect of variations in technological capabilities delineated by established Measures-Of-Effectiveness, and the ability to map 'Technologies' into 'Capabilities' using an integrated toolset within a PC-laptop environment configured for first-order design parameter evaluations. The result is a methodology for determining Key Performance Parameters (KPPs) relevant to a parametric aerospace system design space.

IV. Conclusion

In this paper, we have presented a flexible methodology for exploring design spaces for conceptual vehicles. The flexibility allows plugging in simulation tools as well as analysis tools of different fidelities. In this context, FLAMES has shown itself to be a valuable tool in our conceptual design environment. The application of the methodology, including analysis of synthesized vehicles operating in a simulation environment, demonstrates the ability of multi-disciplinary analysis and optimization (MDAO) to capture interactions of vehicle and weapon parameters and the impact on mission effectiveness. MDAO is an important part of determining required performance criteria as well as identifying optimal system solutions

This treatment of aircraft conceptual design as a system of systems (aerodynamic surfaces, propulsion system, control system, weapons systems) design problem is naturally extended to include more systems (sensors, communications, tactics, etc.) and to a heterogeneous mix of assets (ground forces, fighters, bombers, satellites, etc.) in realistic scenarios. Automation within this process enables coverage of large design spaces so that configuration selection is based on reliable data, and then supports subsequent optimization activities.

Acknowledgments

This work was partially supported under the Wright Brothers Institute Contract WBSC9015B. The authors would like to thank Dave Brown at AFRL who managed the program. Thanks also go to Professor Dimitri Mavris and Dr. Patrick Biltgen at Georgia Institute of Technology for their work on munitions, movement, and sensor models and the Battle Manager software.

References

[1] Phoenix Integration, "ModelCenter™7.0 Online Documentation," 2007.

[2] Engineous Software, "iSIGHT™User's Guide, Version 10.0," Oct 2006.

[3] AVID, "ACS™User's Guide, Version 4.1," Jul 2007.

[4] Ternion, "FLAMES™Online Documentation, Version 6.1," 2007.

[5] D'Urso, S. J., "Configuring Tactical Aircraft," *AIAA Paper* 90-3305, 1990.

[6] Matthews, D. F., "The New Joint Capabilities Integration Development System (JCIDS) and Its Potential Impacts upon Defense Program Managers," NPS-PM-04-017, Dec. 2004.

[7] Rubbert, P., "CFD and the changing world of airplane design," *ICAS Proceedings, 19th Congress of the International Council of the Aeronautical Sciences*, Sep 1994.

[8] Zink, P., DeLaurentis, D., Hale, M., Volovoi, V., Schrage, D., Craig, J., Fulton, R., Mistree, F., Mavris, D., Chen, W., Rhl, P., Lewis, K., Koch, P., Cesnik, C., and Simpson, T., "New Approaches to High Speed Civil Transport Multidisciplinary Design and Optimization," 2000.

[9] Anderson, B. H., Baust, H. D., and Agrell, J., "Design-of-experiments to reduce life-cycle costs in combat aircraft inlets," *National Aeronautics and Space Administration, Glenn Research Center*, Jan 2003.

[10] Gatzke, T. D., Dowgwillo, R. M., and Ikeda, Y., "The Design of an Aerodynamic Fairing Using Viscous Computational Fluid Dynamics," *AIAA Paper* 98-2787, 1998.

[11] DeLaurentis, D., Mavris, D., and Schrage, D., "System Synthesis in Preliminary Aircraft Design Using Statistical Methods," 1996.

[12] DeLaurentis, D., Calise, A., Mavris, D., and Schrage, D., "Generating Dynamic Models Including Uncertainty for use in Aircraft Conceptual Design," *AIAA 97-3590*, 1997.

[13] Van der Velden, A., "CAD to CAE Process Automation Through iSIGHT-FD," *Proceedings of ASME Turbo Expo*, May 2007.

[14] Biltgen, P. T. and Mavris, Dimitri, N., "A Methodology for Capability-Focused Technology Evaluation of System-of-Systems," *AIAA Paper* 07-1331, Jan 2007.