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Methodology for Assessing Survivability Tradeoffs in the Preliminary Design Process

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Abstract

Aircraft survivability is a key metric that contributes to the overall system effectiveness of military aircraft as well as to a lower life cycle cost. The aircraft designer, thus, must have a complete and thorough understanding of the interrelationships between the components of survivability and the other traditional disciplines as well as how they affect the overall life cycle cost of the aircraft. If this understanding occurs, the designer can then evaluate which components and technologies will create the most robust aircraft system with the best system effectiveness at the lowest cost. A synthesis and modeling environment is formulated and presented that will allow trade-off studies and analysis of survivability concepts to be conducted. This environment then becomes the testbed used to develop a comprehensive and structured probabilistic methodology, called the Probabilistic System of System Effectiveness Methodology (POSSEM), that will allow these trades to be conducted. Initially, consideration of the survivability discipline will be restricted to components of aircraft susceptibility. The methodology is presented here in its formative state, with primary issues being identified and tentative solutions presented. A theater level test case of susceptibility trades is presented.

Introduction

In the current world military environment, system effectiveness takes on a new meaning. In the past, military aircraft design has been characterized by an emphasis to design for optimum performance. Aircraft success was defined in terms of the aircraft's ability to perform at least as well as the requirements to which it was designed, including adaptability to rapidly changing threat environments. Recent imperatives, however, have shifted the emphasis from performance to overall system effectiveness as a key measure of merit for the aircraft. Today, system effectiveness must not focus only on the aircraft's performance, but instead on its ability to satisfactorily complete its mission, against a wide variety of threats and situations, at an affordable life cycle cost.

Until recently, preliminary aircraft design focused on tradeoffs between the traditional disciplines: aerodynamics, propulsion, structures, etc. However, issues such as technological advances and life cycle considerations have induced a shift of emphasis in preliminary design to include non-conventional disciplines. These disciplines, often called the "-ilities", include subjects like maintainability, reliability, and safety, as well as crossover disciplines such as economics and stability and control. One of these disciplines is that of survivability, primarily of concern with military aircraft. The creation of such entities as the Joint Technical Coordinating Group on Aircraft Survivability (JTCG/AS), whose primary goal is to advance and establish the design discipline of survivability[1], indicates the growing importance of this new field.

Survivability is defined by Ball to be "the capability of an aircraft to avoid and/or withstand a man-made hostile environment"[2]. This capability is measured by the parameter P_s, the probability of survival, which in turn is related to the probability of kill, P_k, by the following relationship:

$$P_s = 1 - P_k$$

The probability of kill is the product of two key survivability concepts: susceptibility and vulnerability. Susceptibility is the probability that the aircraft will be detected and hit, and is a function of those things that would make the aircraft more difficult to be seen and tracked, such as stealth, maneuverability, tactics, and advanced avionics. Vulnerability, on the other hand, concerns itself with the probability that the aircraft will be killed if hit. This makes vulnerability a function of detailed aircraft design, including specific armament, system locations and redundancies. Much work has been done in the area of vulnerability reduction, with susceptibility becoming more of a major concern in recent years primarily in the development of today's stealthy aircraft, such as the Lockheed Martin F-22. Because these survivability concepts are themselves functions of basic design parameters and requirements, as are the other more traditional design disciplines, it becomes both necessary and cost-effective to consider survivability as a design discipline in its own right, allowing tradeoffs to occur at the preliminary design stage, thus optimizing the aircraft to an overall system effectiveness metric with a resulting reduction in design cycle time.

The Importance of Survivability

Survivability is important on several levels. As a function of worldwide military conflicts, political instabilities, economic uncertainties, increasing defense budget constraints, and the high cost and sophistication of modern military aircraft, we are being asked to do more with less[3]. Our forces are being asked to generate more sorties for more diverse missions with fewer assets. Each aircraft is experiencing increased utilization. An aircraft that is more survivable is, in general, safer and more reliable during peacetime operations. In turn, a safer, more reliable aircraft has a reduced overall life cycle cost and is thus more affordable. This concept is shown in Figure 1.

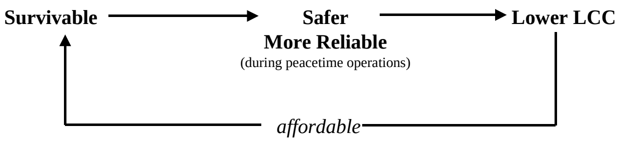


Figure 1- Relationship between Survivability and LCC

During conflicts, an aircraft that is more survivable has a greater chance of fulfilling its mission and returning safely to base. This increases its probability of success for any given operation, as well as allowing the aircraft to remain a useful and viable tool for future missions. More importantly, the more survivable an aircraft is, the greater chance its pilot and crew have of returning unscathed. The moral, societal, and economic cost of losing a trained pilot or crewmember is tremendous.

An interesting study was done with Desert Storm data that illustrates the effect that enhancing survivability can have. The study showed that when P_s changed from 98% to 99%, the changes in surviving force go from 36% to 60% (51 sorties). For 100 aircraft, a Ps of 98% allows 3151 targets while a Ps of 99% allows 3970 targets. Therefore, a 1% increase in survivability gives a 26% increase in force effectiveness[3]. In other words, linear changes in survivability produce exponential changes in force effectiveness.

Finally, it is important to note the expense of trying to add survivability features to an existing aircraft. The addition of many survivability concepts often involve a compromise with other features. For example, an aircraft that sports an ideal configuration for stealth could be inefficient aerodynamically and may need to rely on sophisticated and expensive control systems. In addition, adding survivability features later often substantially increases aircraft weight, reducing performance and economic viability. By considering survivability as a discipline during the preliminary design process, these trades can be optimized and their effects analyzed, at potentially considerable savings in cost.

System of Systems Effectiveness

Given the importance of survivability as a design discipline, the question now becomes: how can survivability be incorporated into the preliminary design process? In order to successfully include survivability features into a design, the *effect* of these features must be identified and quantified early enough in the design process to allow for sufficient trade-offs and resource allocation. The methodology presented here proposes that in order to properly assess the effect of survivability features, the analysis must be conducted at a level higher than that of the aircraft. The analysis should take place at the theater level, making the problem a system of systems investigation.

The Aircraft as the System

The Aerospace Systems Design Laboratory (ASDL) at the Georgia Institute of Technology has formulated probabilistic methodologies that treat individual aerospace concepts as the system[4,5,6,7]. These methodologies revolve around the creation of meta-models, based on regression methods, that relate vehicle design variables (geometry, engine specifications, drag polars, etc.) to vehicle responses (takeoff gross weight, thrust-to-weight ratio, etc.). Further advances in the methodology added economic variables, requirements and mission constraints, as well as analysis of the effect of new technologies. In this way, the aircraft itself was treated as the system, and aircraft Measures of Performance (MOPs) were the metrics used to assess the "goodness" of the system (Figure 2). System effectiveness, therefore, was a function only of that aircraft's design variables and parameters.

While this method of analysis resulted in the design of a vehicle that was optimized to its own mission and performance requirements, the vehicle remained independent of its role in the larger system: the theater. In other words, the aircraft was never placed in its correct context and evaluated as system fulfilling its intended function.

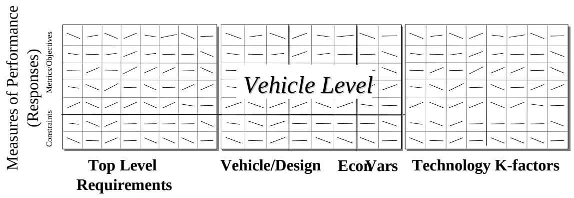


Figure 2-Analysis of the Aircraft as the System[8]

The Theater: System of Systems

In order to place the aircraft in its correct context, the system must be redefined. No longer is the aircraft the system; rather, the theater becomes the system, and the aircraft is relegated to being a component of this new system. The theater thus becomes a system of systems and is a function of the vehicle-level components of the larger system, including the aircraft.

There is, however, a missing level in this formulation. The outputs of the vehicle level (performance parameters) do not usually map directly as the inputs to theater level modeling codes. Rather, the inputs at the theater level usually consist of probability of kill values or effectiveness values for component vs. component encounters. There must be an intermediary mapping that takes the outputs of the vehicle level as its inputs, and in turn generates outputs that serve as inputs to the theater level. This is illustrated in Figure 3. Theater level Measures of Effectiveness (MOEs) are functions of vectors of subsystem Measures of Performance, which in turn are functions of subsystem requirements, design and economic variables, and technology factors.

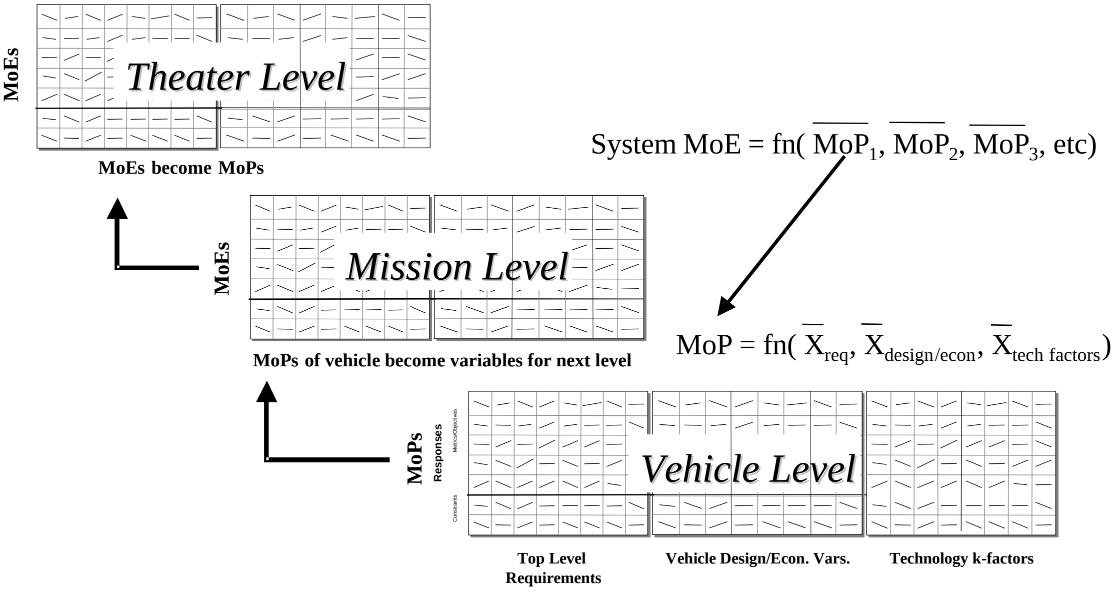


Figure 3- Mapping and Sensitivity Cascades Relating Vehicle Characteristics to Theater Level MoEs

When the methodology is complete, there will exist a continuous mapping between vehicle level design parameters and theater level Measures of Effectiveness. Changes at the vehicle level can thus be propagated all the way to the theater level. Instead of optimizing an aircraft, for example, to its own pre-defined performance and mission constraints, the aircraft can now be optimized to fulfill theater level goals and objectives. In addition, as more system level components are treated as input variables, tradeoffs can be established not only at the individual component level, but *across* the components. In other words, the methodology will allow tradeoffs between, say, the effectiveness of a cruise missile compared to an aircraft carrying a specified weapons load. Tradeoffs could also be made between the number of system components needed: two of aircraft “A” could produce the same effectiveness of five of aircraft “B”, but at less cost. Thus, the methodology becomes a key device for design decisions as well as resource allocation.

Finally, the completed methodology can be used to actually determine the mission and design requirements for the vehicles themselves that comprise the system. By using the Measures of Effectiveness at the theater level as a measure of goodness, tradeoffs can be made between vehicle design and mission requirements. These requirements, when optimized to maximize the overall effectiveness of the system, become the requirements to which the vehicles are then designed.

Methodology

The methodology presented here is called the Probabilistic System of Systems Effectiveness Methodology (POSSEM) and can be used to assess survivability tradeoffs during the preliminary design process. The methodology is still in its formative state and will continue to evolve over time. The framework is presented here, along with considerations and analysis challenges that still need to be met. POSSEM is an extrapolation of existing probabilistic and statistical ASDL methods (referenced earlier) and incorporates tentative solutions to issues that are a function of the new theater level analysis. These issues have been summarized in Reference 9. The methodology is shown in Figure 4. The following sections detail each methodology component, including analysis challenges and possible solutions.

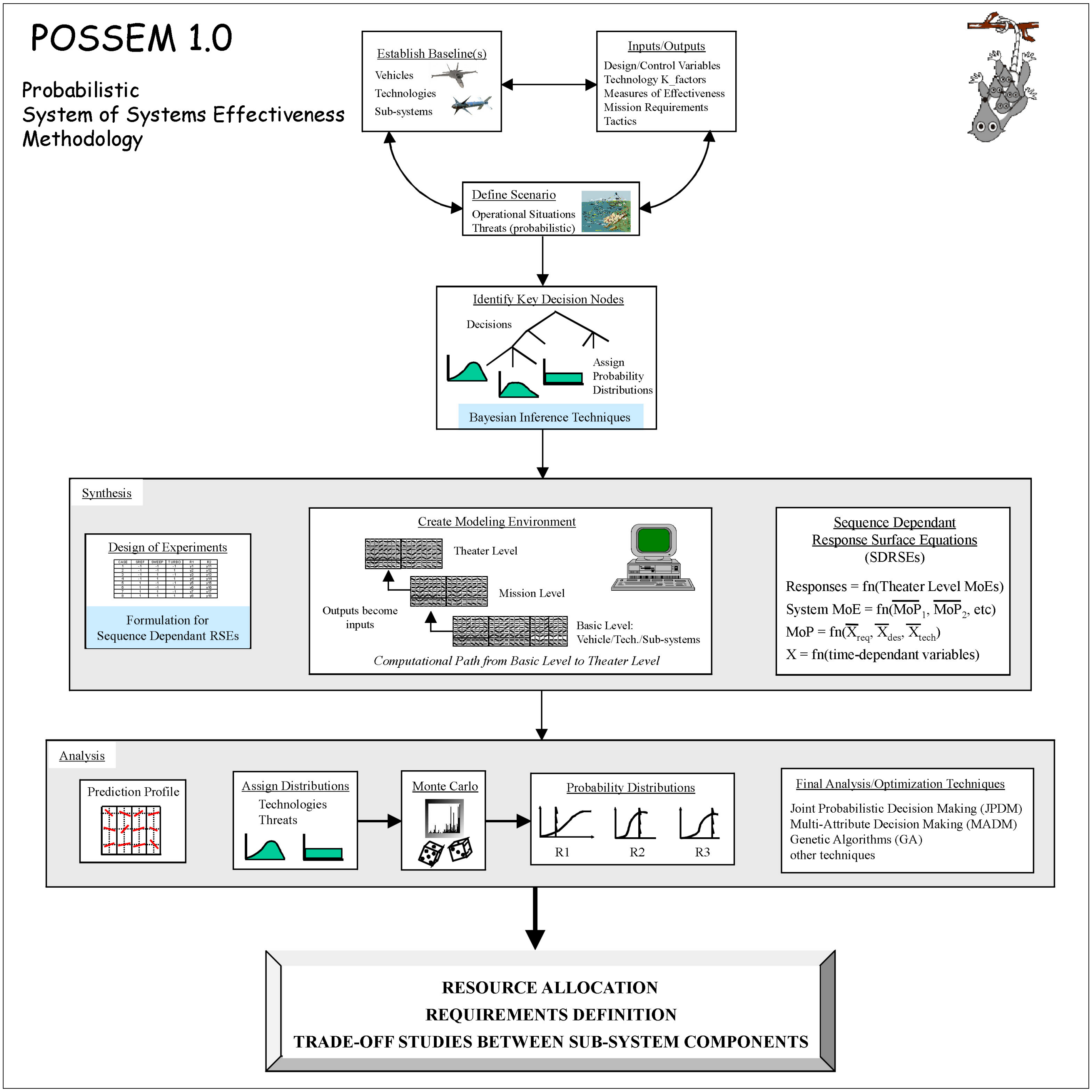


Figure 4- POSSEM: Formulation of Methodology Used to Assess System Effectiveness and Survivability Trades

Defining the Problem

A well-defined problem is the foundation of a successful analysis. There are three main factors that are of consideration in the problem definition phase of POSSEM: establishing the baselines, choosing the inputs and outputs, and defining the scenario. These three things must be established concurrently, as they are each dependant on the others, as shown in Figure 4.

Establish the Baseline(s)

The first step is to establish baselines for the systems of interest. In the survivability case, the baseline would be the aircraft to which the survivability concepts are to be applied, but could also be sub-system components (such as an avionics package), new technologies, or other vehicles, such as missiles or other weapon delivery systems. The purpose of the baseline is to have an established reference point with which to compare results.

Define the Inputs and Outputs

The inputs and outputs are at the heart of the analysis. Inputs must be chosen at the vehicle (or subsystem) level that will allow adequate representation of the concepts and technologies that are to be explored. For code considerations, these inputs must be easily manipulated. Unlike the established methodologies referenced earlier, the outputs will not be at the vehicle level, but rather will be theater level output metrics (Measures of Effectiveness). Careful consideration of both inputs and outputs should be made in order to ensure that the outputs are meaningful functions of the inputs. A screening test is helpful for this step.

Define the Scenarios

A scenario and/or operational situation must be defined that captures both the input parameters as well as the outputs. The scenario must be suitably complex to model all significant interactions, yet be free from unnecessary, and sometimes confusing, detail. For example, the initial scenario defined in Reference 9 modeled four SAM sites protecting a single airbase. However, the geometry of the problem caused only one SAM site to be activated by the flight path of the aircraft. All four SAM sites were carried through the analysis, increasing code run time and complexity. A simple geometric pre-analysis would have identified the problem earlier, and changes in both input and output could have been made.

For the survivability case, the threats are of paramount importance. Indeed, the definition of the threats drive the survivability solution! By defining the threats in careful conjunction with the inputs and outputs, a useful analysis will result. A more comprehensive method is to treat the threats probabilistically. By allowing the threats to vary (within reasonable bounds), the vehicle is optimized to a more robust solution. A probabilistic threat environment is inherent to POSSEM.

The “Human in the Loop” Problem

A major difference between vehicle level and theater level analysis codes is how the user interacts with the code. In a traditional vehicle sizing code, the user will supply a set of inputs and the code will iterate on a sizing scheme to converge the vehicle according to the laws of physics and empirical relationships. In many theater codes, however, the user becomes an integral part of the analysis process. This means that the user periodically evaluates the effect of his/her decisions and can then change the parameters (either from that point or change initial input parameters and rerun the simulation) to provide improved results. Figure 5 shows a typical analysis scheme for using a theater level code.

The alternative to having the human in the loop is to use some sort of embedded rules (expert systems) to make decisions. There are some theater level codes that do this. The key drawback to this is that the rules have an inherent lack of flexibility to simulate real operational plans. In addition, these rules lack transparency in assessing cause and effect relationships. An example of this drawback in illustrated in the following example. Say that an embedded rule system is used to model the decisions made in a particular scenario. The results are summarized as follows: “The analysis shows that there is an 85% probability that this scenario (with its inputs) results in the loss of two aircraft carriers in the first four days of the event.” What is wrong with this statement? In the real world, losing two aircraft carriers is so completely unacceptable that, after the loss of the first carrier, **the decisions (inputs) would be changed** in order to ensure that a second carrier would not be lost. With embedded rules, unrealistic results such as these could be modeled and erroneous decisions made.

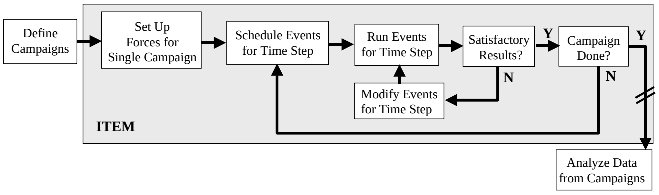


Figure 5- Decision-Making Flowchart for Theater Level Code[10]

Decision Nodes

The question now becomes: how do we apply a probabilistic methodology if we need to maintain the information provided by having human in the loop? First, the scenario is examined and key decision nodes are identified. The concept of decision trees is useful here, and can aid in identifying the impact of key decisions.

In addition to using decision trees to identify and model key decision points, the concept of Sequence-Dependant Response Surface Equations (SDRSEs) will be explored, and is discussed in a subsequent section.

Another advantage of this formulation is that probability distributions could be applied to each possible path at each node. In this way, the human decision maker can be modeled. For example, a decision node may have two identified paths. A “practical” decision might have, say, an 80% chance of occurring while a more “aggressive” decision would only be chosen 20% of the time. In this way, one could model the personalities and decision-making abilities of several different types of decision makers, but with the ability to assess them in one modeled environment. Bayesian inference techniques will be explored to aid in the determination of the distributions.

The Synthesis Environment

POSSEM needs to have at its heart a synthesis environment to operate upon. As discussed earlier, the analysis needs to be conducted at three levels: the vehicle (or subsystem) level, the mission level, and the theater level. Appropriate synthesis codes that represent these three levels must be identified. In addition, the outputs of the vehicle level code must be compatible with the inputs of the mission level code, and the outputs of the mission level code must be compatible with the inputs of the theater level code. Finally, a seamless integration between the three (or more) codes must be created.

Response Surface Methodology

Response Surface Methodology (RSM), in conjunction with a Design of Experiments (DoE) formulation, is then applied to the linked synthesis codes. RSM is an efficient, multivariable approach to system modeling that defines clear cause-and-effect relationships between design variables and system responses, and is based on a statistical approach to building and rapidly assessing empirical metamodels[11,12].

The RSM methodology, employing a DOE strategy, creates metamodels of a particular synthesis code by selecting a subset of all possible combinations of variables to run which will guarantee orthogonality (i.e. the independence of the various design variables). Using regression techniques, the subset of inputs are related to the selected outputs to create an equation that represents the relationship between inputs and outputs of the synthesis code. This technique allows the maximum amount of information to be gained from the fewest number of experiment executions, and thus provides trade study results in a more cost-effective manner.

Sequence Dependent Response Surface Equations

Because probability distributions were placed around the key decision nodes, the resulting metamodels mapping outputs to inputs will also be probabilistic in nature. A sequence dependant response surface equation (SDRSE) would model an input variable that changes during the course of the analysis. Instead of the response being a function of a set of variables, the response would be a function of a *vector* of variables. Each vector would represent the set of decisions that could be made at each decision node. The precise formulation of these SDRSEs remain a current research issue.

Final Analysis

The final analysis consists of several tools that together provide useful information to the designer and decision-maker. The first of these is the prediction profile, generated by a statistical analysis package called JMP[13]. The prediction profile is a graphical representation of the response surface equations, showing how the responses vary with respect to each variable. In essence, the sloped lines depict the partial derivatives of the response with respect to the variable with all other variables set to their nominal value. JMP allows the designer to change the value of the variables by using a click and drag technique. The graph is then updated in real time, showing the new values of the responses, which are the effects of the changes. The designer can thus manipulate the equations to gain insight into the problem and also seek optimal configurations.

If probability distributions are assigned to the initial input variables, a Monte Carlo analysis can be conducted utilizing the RSEs. Remember that the inputs can represent geometric changes or infused technologies. By creating a probability distribution around the values (taking care that the ranges of the distribution fall inside the range of the computed RSEs), families of designs can be considered and analyzed. The results of the Monte Carlo analysis are probability density functions (PDFs) and their integrals, the cumulative distribution functions (CDFs) which show the probability or confidence of achieving a certain value. The designer can interpret information from the probability distributions in a number of ways. If the distribution has quite a bit of variability, but some or most of it fulfills the requirement being examined, this would suggest that the assumptions, including any technology infusions, are viable. It would be beneficial, therefore, to invest more resources into the technologies or options that the assumptions represent. This addition of resources could have the effect of narrowing the uncertainty associated with the technologies or options. On the other hand, if the distribution indicates that the probability of meeting the requirement is low, then it might be more provident to examine other options before investing money into a technology or decision that might not be sufficient to solve the problem. This kind of system-level investigation can also show how much the detrimental effects of certain decisions are penalizing the system. This information, shared with the disciplinary experts that engage in the development of the technologies or assumptions, could be investigated to see how resources need to be allocated towards reducing the penalties, as opposed to improving benefits.

There are several other techniques that may be employed at this point to conduct further analysis and optimization. The first of these is a technique pioneered at ASDL called Joint Probabilistic Decision Making (JPDM)[14]. This technique combines multi-criteria into a single metric, the probability of success. POSSEM will initially explore JPDM as the primary decision making process in the methodology.

Theater Level Application

Although POSSEM may theoretically be applied to any complex system of systems, the survivability test case was chosen as a proof of concept of the methodology. Specifically, susceptibility tradeoffs were desired. In Reference 9, the basic, existing methodology was applied to the theater level only and was used to aid in the identification of methodology issues. Those issues have been identified and POSSEM proposed. The next step was to implement the methodology again at the theater level, this time using inputs and outputs that model a survivability scenario. Again, this step is used to identify any specific survivability issues that need to be addressed in the methodology. Also, the results from this example will be used to help identify mission level codes that will be needed for the synthesis step of the process.

Problem Definition

The first step of the example process was to define the problem. As shown in the POSSEM flowchart, defining the baseline(s), scenario, and inputs and outputs is an iterative process. For this case, susceptibility tradeoffs were key. Therefore, a scenario was needed that would allow effective modeling of baseline vehicles and technologies as well as enable susceptibility tradeoffs to take place. In addition, variables are limited to those available in the theater level code of choice.

Baseline

It was decided to model two notional aircraft with different susceptibility and performance features. One aircraft would be a stealthier, more maneuverable aircraft that would have a limited weapons load. The other aircraft would have a substantial weapons load capability, but would be slower, less agile, and less stealthy. The weapons themselves would have identical capabilities, but the number of weapons carried by each aircraft would differ. In addition, the aircraft were differentiated by mission duration and turnaround time. The aircraft are compared in Figure 6.

		Strike 1	Strike 2
no factor	Mission Duration (hrs)	5	4
no factor	Turnaround Time (hrs)	0.5	1
	Speed (kts)	500	350
no factor	Range (nm)	700	600
	Detectability	Variable	0.8
	Maneuverability	Variable	0.8
	Load		
	SCL1	4 ATG-1, 4 ATG-2	8 ATG-1, 8 ATG-2
	SCL2	4 ATG-2, 4 ATG-3	8 ATG-2, 8 ATG-3

Note: All weapon capabilities (ATG-1, ATG-2, ATG-3) are identical

Figure 6- Comparison of Notional Strike Aircraft Used in Study

Scenario

Because aircraft were selected as the baselines, an unclassified notional air superiority scenario was chosen. The scenario needed to be simple enough to be able to clearly identify results of tradeoffs (especially since this first case is a proof of concept) yet complex enough to capture important interactions between variables. An extrapolation of the basic scenario used in Reference 9 was chosen. This scenario models a situation in which South Florida attacks North Florida and is shown in Figure 7. Two airbases are established in South Florida and the notional aircraft stationed there. The target is an airbase in North Florida that is protected by four SAM sites.

The SAM sites are distributed around the airbase. Each sites has identical features, including the same number of launch rails, reload time, antenna height, and engagement radius. However, there are two different kind of weapons defined that differ in terms of range, speed, and altitude (Figure 8). Two of the airbases have one type of weapon and the other two have the second type.

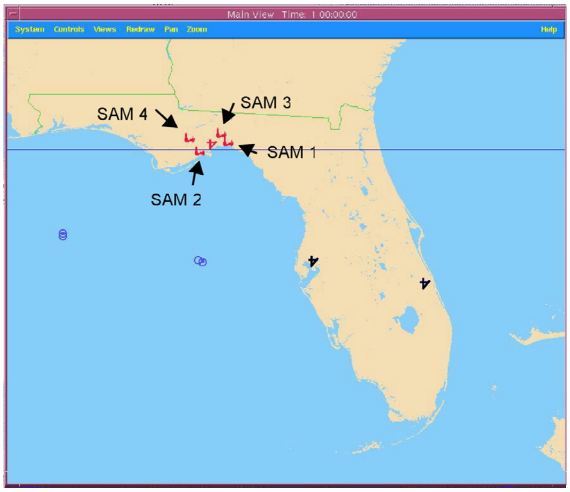


Figure 7- Florida Scenario

	Weapon	RSAM-1	RSAM-2
	Min Range (nm)	2	1
	Max Range (nm)	20	15
	Speed (kts)	600	800
no factor	Min Alt (ft)	2000	1000
no factor	Max Alt (ft)	18000	14000
	Rel. Detectability	0.5	0.5
	Ph	0.9	0.9
	Engagement Time (min)	1.5	0.5

Figure 8- SAM Site Weapon Comparison

Features of the South Florida (Blue) airbases are not crucial to the study. The two notional aircraft are assigned to each Blue airbase and a surplus of weapons are available. The North Florida (Red) airbase features runways, shelters, revetments, and aircraft in the open. These aircraft do not mobilize to defend the airbase, but are rather targets. The only defense of the Red airbase comes from the surrounding SAM sites.

The air campaign consists of hourly attacks on the Red airbase for a total of 8 hours. Blue airbases alternate attacks, so each airbase launches a total of four strikes, consisting of five aircraft per strike mission. Each aircraft is assigned one of five targets: a SAM fire control, a SAM radar, a runway, a shelter, or aircraft in the open. Flight paths are straight line from airbase to airbase. SAM sites and Red airbase features are allowed a variable repair rate. There is no repair rate for Blue aircraft. SAM sites defend automatically when detecting incoming aircraft.

Inputs and Metrics of Effectiveness

Input choices were limited to those available in the synthesis code. Those variables most closely modeling susceptibility/survivability concepts were chosen. For aircraft, the variables selected were detectability, maneuverability, and turnaround time. The detectability variable models the relative detectability of the aircraft, and is a scaling factor used to reduce the probability of detection of opposing forces against the aircraft. Likewise, the maneuverability variable measures the aircraft's ability to evade defensive systems and is a scaling factor used to reduce the probability of hit of engaging weapons against the aircraft[15].

Because POSSEM assumes a probabilistic threat environment, several threat variables were chosen. The engagement range of SAM sites is allowed to vary, but all four sites vary at the same time. Additionally, repair rates for the SAM fire control and radar systems, as well as airbase runways, shelters and aircraft in the open were selected as variables of interest. Table 1 summarizes the variables and their ranges.

Table 1- Input Variables for Study

Values	Low	Baseline	High
Detectability Strike 1	0.7	0.5	0.3
Detectability Strike 2	1	0.8	0.6
Maneuverability Strike 1	0.6	0.4	0.2
Maneuverability Strike 2	0.9	0.7	0.5
Turnaround Time Strike 1	0.25	0.5	0.75
Turnaround Time Strike 2	0.75	1	1.25
Track Range SAM Site	10	20	30
Repair Rate SAM Fire Control	0.1	0.2	0.3
Repair Rate SAM Radar	0.1	0.2	0.3
Repair Rate Runways	0.1	0.2	0.3
Repair Rate Shelters	0.1	0.2	0.3
Repair Rate A/C in Open	0.1	0.2	0.3

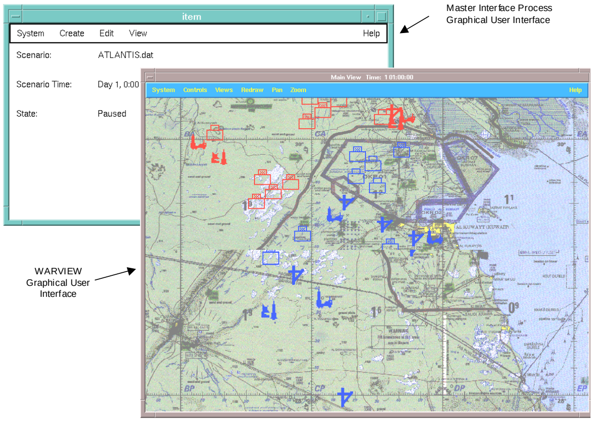
Appropriate output Measures of Effectiveness were chosen to illustrate the effect of the changing variables. The surviving percentage of each aircraft is tracked, as well as the number of each type of SAM weapon fired. Finally, the number of runways and aircraft in the open destroyed was tabulated. These outputs are shown in Table 2.

Table 2- Output Variables for Study

Outputs
% Survival of Strike 1 Aircraft
% Survival of Strike 2 Aircraft
Number of RSAM-1 Weapons Fired
Number of RSAM-2 Weapons Fired
Number of Runways Destroyed
Number of Aircraft in the Open Destroyed

Synthesis

Because this study was conducted only at the theater level, only a theater level code was utilized. The code selected was the Integrated Theater Engagement Model (ITEM)[15]. ITEM is an interactive, animated computer simulation of military operations in theater-level campaigns. It has fully integrated air, land, and naval (including amphibious) warfare modules and contains a strong emphasis on visualization. The inputs and output are GUI-driven (Graphic User Interface), and an example of this interface is shown in Figure 9. ITEM is fully object-oriented in design and execution and contains a hierarchical structure of its database.



Scenario: ATLANTIS.dat

Scenario Time: Day 1, 0:00

State: Paused

Master Interface Process Graphical User Interface

WARVIEW Graphical User Interface

Figure 9- The ITEM Graphical Interface and Environment

Because this test case is a proof of concept for using POSSEM to assess survivability tradeoffs, the Sequence Dependent Response Surface Equations were not implemented (and, as discussed earlier, have not been fully developed yet). A standard Design of Experiments was utilized to produce conventional Response Surface Equations. At this time, the RSEs are functions of the theater level inputs discussed earlier. As the project progresses, codes will need to be identified that map aircraft geometry and performance metrics to the identified theater level inputs.

Theater Level Study Results

Figure 10 shows the prediction profile for the survivability test case. The first thing to notice is that none of the repair rates for the airbase components have a significant effect on the responses. This is shown by a relatively flat line. There is a slight slope on the repair rate for runways when compared to the number of runways destroyed that does show a small effect of increasing runway repair rate and decreasing number of runways destroyed. If the variable ranges on the repair rates had been increased, or the air campaign plan decreased, the repair rate could have had more impact. The same result is seen with turnaround time for the two aircraft. The range around turnaround time was just too small to have an impact, given the air campaign plan.

Track range for the SAM sites shows considerable effect on the responses. As the track range increases, more weapons are fired, and more aircraft are killed. This is logical and intuitive. In addition, the destruction of the airbase components decreases. Note the deflection of the runway response to track range at its aft end. This indicates that the runway destruction begins to increase in rate towards the end of the air campaign. This could indicate that SAM site damage has an effect on its ability to protect the airbase components. Interestingly, more SAM-2 weapons are fired at the aft end of the campaign, and the number of SAM-1 weapons appears to decrease slightly.

Maneuverability can be seen to have a slight effect on the number of airbase components destroyed, with the Strike 2's maneuverability playing a slightly more significant role. Because maneuverability primarily affects the interaction between aircraft and SAM site, this result is somewhat intuitive. Once the aircraft has penetrated the defenses successfully, the maneuverability ceases to affect the actual kill. But it is interesting to note that increasing the maneuverability of Strike 2 (the slower, higher load-carrying aircraft) has a more significant impact than increasing that of Strike 1. Increasing the maneuverability of both aircraft does have a direct impact on the survivability of that aircraft.

Detectability shows less promise. For Strike 2, increasing the detectability has negligible effect on the airbase components destroyed, as well as no discernable effect on increasing its survivability. For Strike 1, increasing its detectability does have a small impact on the number of airbase components destroyed and a small, interesting impact on its own survivability.

Overall, it was discovered that the air campaign plan had a significant effect on the quality of the results. Force mix was tried as a variable and was found to depend too heavily on the specific order of air strikes. This points to significant interactions in the code that need to be explored more fully. For a very simple air campaign, it was shown that increasing the percentage of Strike 1 aircraft in the overall number of aircraft did increase that aircraft's survivability. However, this increase decreased the survivability of the Strike 2 aircraft, and at a more significant rate. This concept of force mix is an interesting one that will be explored further in the development of the overall methodology.

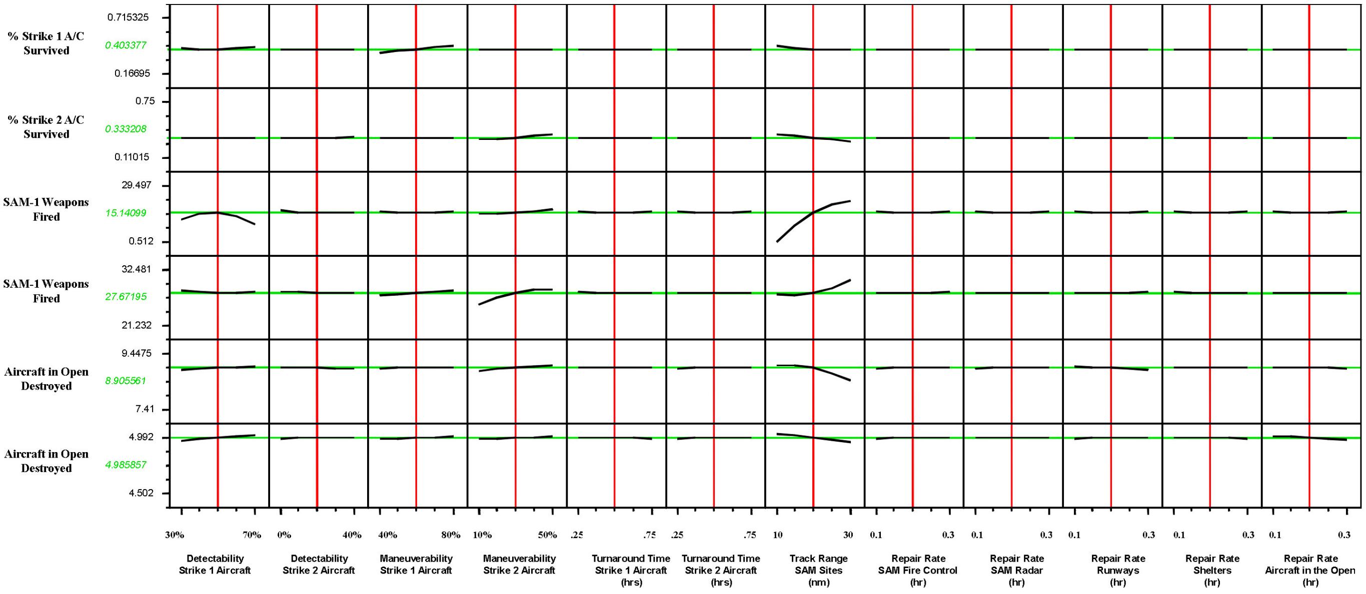


Figure 10- Prediction Profile for Survivability Test Case at Theater Level

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