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APPLICATIONS OF DISCRETE EVENT SIMULATION MODELING TO MILITARY PROBLEMS

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ABSTRACT

The military is a big user of discrete event simulation models. The use of these models range from training and wargaming their constructive use in important military analyses. In this paper we discuss the uses of military simulation, the issues associated with military simulation to include categorizations of various types of military simulation. We then discuss three particular simulation studies undertaken with the Air Force Institute of Technology's Department of Operational Science focused on important Air Force and Army issues.

1 INTRODUCTION

Military analysis relies heavily upon models to gain insight into the myriad of issues facing the military. Some of the critical issues facing the military in the aggregate include: how to structure the military given the uncertainty of the future; how to maintain a viable military-industrial complex given the uncertain future; and how to allocate limited defense dollars among the services. Within each military service important issues include: how to allocate, train, and equip forces to meet demands placed on that service; what types and numbers of weapons and weapon systems to procure and maintain in the future; and how to allocate limited service budget allocations among the diverse demands for those monetary resources.

The DoD defines a model as "a physical, mathematical, or otherwise logical representation of a system, entity, phenomenon, or process" (Davis, 1995). The military does not rely on one type of model. The military regularly employs mathematical models for resource allocation. Physical models are used for experimentation and extensive testing. Virtual reality simulations are used to provide decision makers an environment to examine issues ranging from design to tactical battlefield management. Human-in-the-loop and distributed simulation systems are a crucial aspect of military training. Finally, constructive simulations are used extensively among each of the military services affecting all aspects of the military, from budgets and acquisitions, to force structuring and deployments. Our focus in this paper is on the use of constructive, or analytical, simulation, for military-specific problems.

This paper is organized as follows. We first discuss some broad issues associated with discrete event simulation modeling applied to military problems. We then provide an overview of some of the general purpose combat simulations in use within the United States Air Force. We then close with discussions of recent discrete event simulations built to address particular problems facing the Air Force and the Army.

2 ISSUES IN MILITARY SIMULATION MODELING

Military simulation falls into three broadly defined categories. These categories are: live, virtual, and constructive simulation. As explained in Davis (1995), "live simulations involve real people using real systems." These are best characterized as field exercises. Next, "virtual simulations involve real people using simulated systems." These can be thought of as flight simulators or virtual environments. These types of simulations also include combined exercises where real people, using real systems, interact with and react to the actions of simulated people or systems. Finally, "constructive simulations are what we usually think of as models, war games, and simulations." Constructive simulations are the focus of this paper and are considered to be contained within the computer with the potential for some limited human input.

Constructive simulations can be viewed, or classified, along a number of dimensions. A simulation may be *dynamic* or *static* depending upon whether the passage of time is explicitly considered or not considered, respectively. Simulations can be *continuous* or *discrete* depending upon whether state variables within the model change at any time in the model or at discrete points in time, respectively. A *deterministic* simulation contains no random components while a *stochastic* simulation explicitly incorporates uncertainty via probability distributions. A simulation might also be categorized in terms of how the results are used. A *descriptive* simulation model is meant to describe a military process and this is generally accepted as the primary use of simulation. However, a simulation might also be used for prescriptive purposes such as in a simulation optimization application where the results of the analysis are intended to provide a set of "best settings," or the simulation results help form the basis for decision recommendations. Other classifications deal with the overall structure and managerial use of the simulation.

A key issue in military constructive simulation models is where that model is used within the organization. The military is a hierarchical organization with delineated chains of commands. Organizations lower in the hierarchy are naturally more concerned with operating details such as when specific parts are going to arrive so that maintenance can proceed or when is the helicopter going to deliver the meals and additional supplies needed by the deployed troops. These issues occur more rapidly and frequently than decisions at higher levels of decision-making. Models supporting decision making on this lower level will necessarily require more detailed modeling of a fairly specific aspect of the military. For instance, a model focused on air operations at the unit level might well be interested in detailed terrain required for "mission rehearsal."

Conversely, organizations higher in the organization are concerned with broader issues such as how to initiate and maintain a supply system for delivering parts and supplies to the various units and organizations within a given area of responsibility. These types of decisions occur less frequently, cover a longer period of time, but clearly have broader impact and are thus considered more important in a strategic sense. Models supporting decision making on this level will necessarily require less detailed modeling across more aspects of the military than models supporting lower-level organizations. In this case, a model focused on air operations at the theater level might well be interested in where to place those aircraft throughout the theater, how to provide logistical support to those operating locations, and how to allocate missions among the various units within the theater.

3 A HIERARCHY OF MILITARY ANALYTICAL MODELS

The same variety of modeling fidelity finds its way into the analytical uses of constructive simulations. An analyst seeking insight into performance characteristics of a proposed air-to-air missile will undoubtedly want a simulation that, in a very detailed fashion, captures the essential elements of flight dynamics for the aircraft and the missiles, the synergistic effects of aircraft systems and missile performance, and the ability to provide various means of deploying that proposed weapon. Further, that analyst will likely focus attention on that small period of time when the fighter pilot will actually be deploying that missile.

Conversely, an analyst seeking insight into the possible ramifications of a large scale deployment such as Desert Shield/Desert Storm of the 1990s is not going to get bogged down in the flight performance characteristics of each aircraft launched and each missile fired. Rather, that analyst will focus on such things as logistics throughput, effectiveness of squadrons of aircraft, survivability of communications networks, and the dynamics of the simulated battlefield. These issues are of a broader perspective, covering a longer period of time and a greater variety of concerns. The models used by this analyst will be less detailed, more aggregate in nature.

The Department of Defense employs a hierarchy such as depicted in Figure 1 to delineate the varied uses and levels of modeling detailed employed in military constructive simulation models. Constructive models span the range of analytical applications. This range covers the earliest phases of requirements determination for new systems, through acquisition of those systems, which includes the resource determination of how many to acquire, to the actual testing and evaluation of the system in a fielded environment.

The model in Figure 1 employs a hierarchy to represent two dimensions to military constructive model characterization. First, the level of the hierarchy represents the level of modeling detail involved and the length of the modeling time-horizon. The lowest level, *specialty*, includes engineering-level models of systems or system components. It is not unusual for such models to address snap-shots in time, or even focus on minutes of operations. Models in higher levels of the hierarchy increase in modeling aggregation and the length of time modeled. Engagement-level models include physics-level modeling as well as some aspect of human involvement. The time span for such models is on the order of minutes to a few hours. Mission level models are more concerned with the interactions among disparate systems, such as one might find in a particular battle. These models can have components of physics-based models but more often will trade-off the modeling fidelity to increase the scope of systems considered. The time frame for a mission level model is on the order of hours to maybe a few days. Finally, campaign level models are the most aggregate in terms of modeling detail and address the greatest span of time. A campaign model will generally model Army Corps, Air Force Wings or Naval aligned enemy forces. The time span for a campaign level model is on the order of weeks to months.

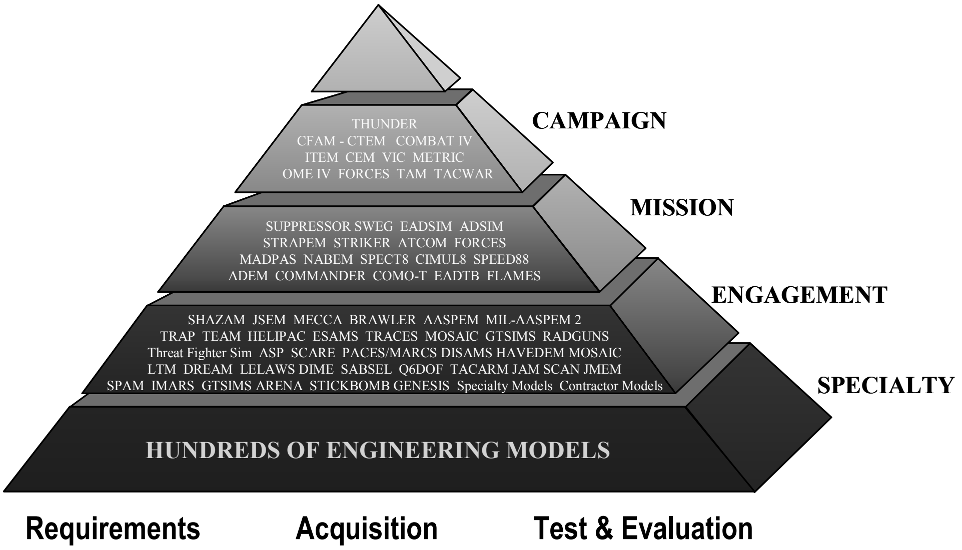

Figure 1: Hierarchy of Models Envisioned in DoD Constructive Simulation

Each level of the hierarchy contained in Figure 1 contains the names of standard models currently being used within the Air Force that fall within a particular hierarchy level.

4 SAMPLE MODELS FROM AIR FORCE STANDARD ANALYSIS TOOLKIT

In an effort to standardize analytical model usage thereby cutting down on new model development for specific purposes, the Air Force created the Air Force Standard Analysis Toolkit (AFSAT). Member models of the toolkit are approved for use in analytical endeavors. In this section we briefly describe three members of the toolkit, each of which are drawn from one of the three upper levels of the model hierarchy in Figure 1.

Brawler is an engagement-level model used for detailed analysis of air combat in both within and beyond visual range. The Brawler model includes physics-based models of aircraft and missile dynamics, radar, radar behavior to include target acquisition, and radar jamming. Brawler also includes a model of individual pilot behavior, the Brawler Mental Model, used to examine various mission and tactical doctrines particularly in light of emerging and envisioned weapon systems.

The Extended Air Defense Simulation (EADSIM) is a many-on-many simulation of air, missile and space warfare. EADSIM falls within the Mission level of the modeling hierarchy. EADSIM models such things as active air defense systems, air-to-air engagements, bombing attacks, and cruise missile attacks. EADSIM is used by analysts to gain insight into issues such as theater missile defense architectures, battle management strategies, force structure analyses, and mission planning.

THUNDER is a campaign-level model used to model conventional land and air warfare at the campaign level of aggregation and timeframe. THUNDER is used to gain insight into such issues as long term expectations of conflicts, course of action assessments, assessments of system contributions to combat capability, and even wargaming. Figure 2 provides a graphic depiction of the many aspects of combat modeled within the Thunder model.

5 FOCUSED, SPECIAL PURPOSE SIMULATION MODELING

Not all military constructive simulation modeling and analysis employ standard models from the AFSAT. Large studies are required to use AFSAT models. However, analyses on more focused issues do have the flexibility of using a specially developed model to gain the necessary insight. In the following sections, we discuss three such modeling efforts from the Air Force Institute of Technology, Department of Operational Sciences.

5.1 An Autonomic Logistics System (ALS) Simulation

The Joint Strike Fighter (JSF) is the next generation of weapon systems designed to meet an advanced threat in the year 2010 and beyond. New concepts are evolving to support this program. One of the revolutionary approaches being presented is the ALS, designed to minimize human intervention by automating logistics support for JSF. The ALS concept injects two major processes in aircraft maintenance and logistics support for aircraft sortie generation: a predictive maintenance component called the Prognostics and Health Management (PHM) system on each aircraft that monitors the onboard aircraft components for faults

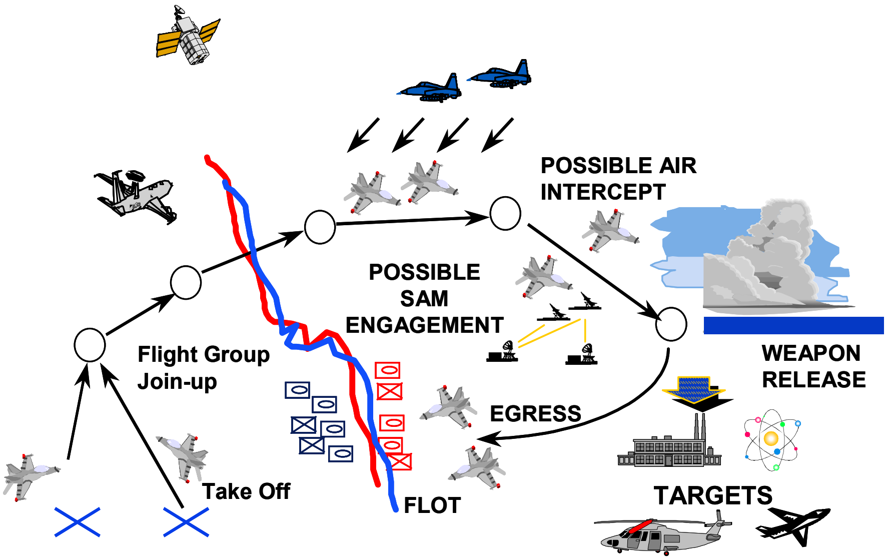

Figure 2: Elements of a Representative Mission in Thunder Campaign Model

and deterioration and the Joint Distributed Information System (JDIS) to transfer information between components in the logistics infrastructure.

A verifiable aspect of the ALS approach is the assumption that time is better utilized through active exchange of information throughout the logistics system, as compared to the reactive response process used by existing systems. This active exchange of information begins with the PHM monitoring the vehicle's onboard system while in flight. As soon as a malfunction or deterioration beyond acceptable limits is detected, the PHM via JDIS informs ground personnel. The ground crew uses this lead-time to locate or order needed parts, gather required tools, and conduct necessary training for complex or unfamiliar installation and checkout of installed parts. In addition, through JDIS, logistics organizations, and contract parts suppliers can monitor aircraft requirements and immediately respond providing required parts to replace the deteriorating or defective component. There is an additional timesaving realized upon the aircraft's arrival. Because the PHM takes control of fault (or impending fault) detection and isolation during flight, maintenance personnel are no longer required to perform this function. As a result, the ground crews have additional time to perform other activities in support of sortie generation. In short, the responsibility for the entire diagnostics process is shifted from the maintenance shop to the PHM component of ALS. Operationally, benefits realized by the integration of PHM include the "virtual elimination of unscheduled maintenance" (Borky, 1998).

Since ALS is a new concept, a model is needed to examine how the system performs and what demands it places on the logistics infrastructure. We identify key elements of ALS and create a computer simulation model of the overall system using object oriented design and the Java programming language. Our efforts focus on the PHM subsystem with rudimentary objects representing other key elements to provide an initial insight into JSF supportability using ALS. With the resulting simulation model we examine the interaction of ALS with the various logistics infrastructures, and analyze overall ALS effectiveness. The model was developed in Java using the Silk simulation package (Healy and Kilgore, 1998)

Object-oriented programming and simulation focuses on capturing the characteristics (i.e. data and operations) of real-world objects and imparting these characteristics into the objects. Figure 3 depicts the classes defined and their interactions. Additional details of the simulation object design and interactions can be found in Rebulanan (2000).

The initial effort focused on building an initial, high-level simulation model of the ALS. The next step was to develop a methodology for adding modeling detail to the PHM component of the ALSim. We approached this by adding a probability of detection curve, variable detection time, and allowing for false positives. While the ideal approach to adding these features involves analyses and models based on actual data, that data is simply not available. To overcome these deficiencies a simulation was developed to generate a PHM component sensor signal suitable for analysis.

The Signal Generator is a very generic simulation that builds a sensor signal. The inputs used to create the simulated signal were gleaned from several journal articles that notionally described how a PHM system operates. The basis for the Signal Generator really comes from the ingested

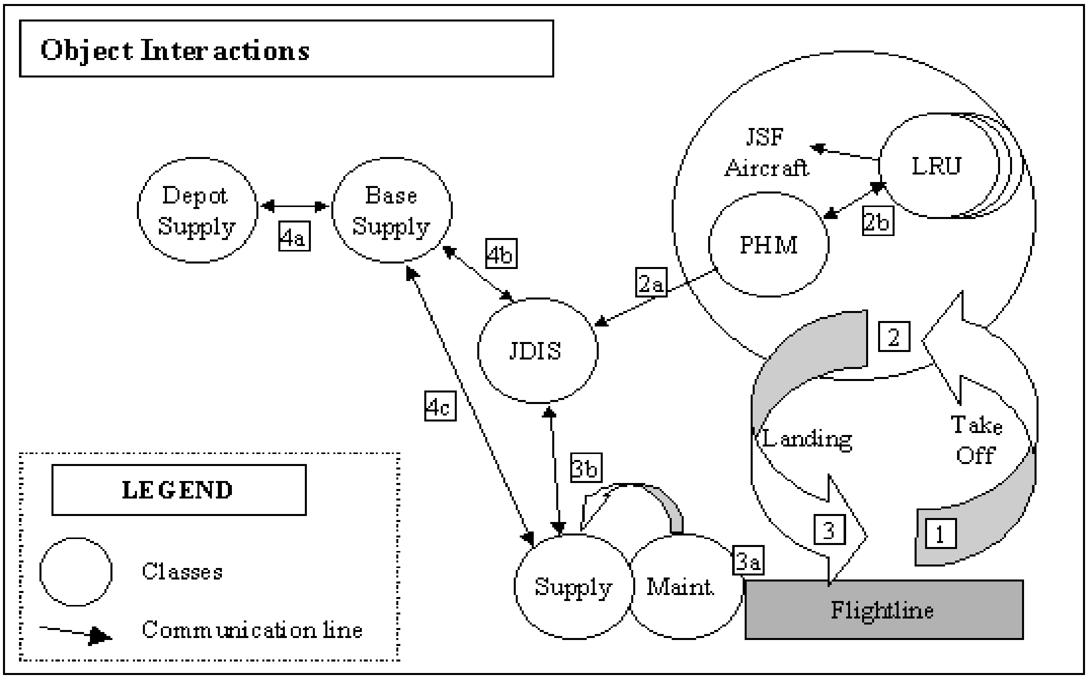

Figure 3: ALSim classes and interactions

debris monitoring system (IDMS) and/or the engine distress monitoring system (EDMS), used for prognostics in the JSF engine to predict mechanical failures (Powrie, 1999).

Once the signal is generated it needs to be analyzed to determine if and when component failure can be predicted. The basic premise is to be able to predict impending failure. Discriminate analysis or building an artificial neural network seem best suited to analyzing the signal data. The basic approach of both analysis methods is discriminating between various populations. In PHM, we differentiate between a component in a healthy state and a component in a failure state. Neural networks tend to have higher accuracy rates than discriminate analysis because neural networks use nonlinear functions. However, predicting healthy versus failing components is currently a one-dimensional problem (sensor signal). With this in mind the neural network analysis and discriminate analysis should lead to similar classification accuracies.

To successfully train (build) a neural network it needs to be exposed to the full range of data. To achieve that goal the Signal Generator was run for 30 replications at component lives varying from 100 hours to 5000 hours, for a nominal case with a MTBF of 1000 hours. Feeding the raw signal data to the neural network is not realistic and furthermore not practical. The raw data is very transient in nature and the purpose of the PHM system is to diagnose the long-term health of the JSF. To put the data in meaningful form, the raw signal is averaged, or batched, over ten signal measurements. The effect of batching is to smooth out the signal. Notionally the batched mean of a healthy component is less than the batched mean of a failing component for our signal. The neural network determines at what value a component can "safely" be classified as operating in a healthy state in contrast to where the component can be classified as degraded or failing.

The resulting neural network is used to build two separate distributions (or two sets of distributions at different realized failure times) to incorporate directly into ALSim. One distribution models the uncertainties in the actual time a failure or degradation is predicted. The other distribution introduces the reality of false positives (predicting a failure or degradation for a healthy component) into the model and allows for modeling the uncertainties in time for these events. These distributions and their parameters are then used within ALSim to more accurately model the uncertainty inherent in the PHM system.

ALS is a new concept yet crucial to the success of the JSF. A key component of ALS is the PHM component. Our efforts to date have centered around building a model of the ALS and PHM components to gain insight into what these concepts offer the JSF in terms of operational capability. A key component of this ongoing research is a signal simulator coupled with data analysis techniques to find those key points where PHM will and will not function as expected. Our goal in identifying those key points is to provide ALS and PHM developers insight into where the primary research emphasis must be placed to leverage research dollars to best effect to attain a true predictive maintenance system for new weapon systems like the JSF.

5.2 Support Equipment Reduction

O'Fearna (1999) examined a simulation-based methodology for reducing the amount of support equipment required by a deploying aerospace combat force. Festejo (2000) extended the effort to account for support equipment reliability. In both efforts, flight-line operations are modeled, aircraft failures occur, and maintenance support resources are modeled within a maintenance process to return combat aircraft to operational capabilities. The Air Force wants to reduce deployment inventories to enable the deploying force to move quicker, since less materiel needs to be moved. The challenge is how to intelligently reduce inventories without impacting the ability of the maintenance function to keep combat aircraft in working order. We model flight line operations and overlay an aircraft failure process. When failures occur specific support equipment resources are requested. Equipment utilization statistics help determine whether inventory levels are correct or need adjustment while statistics pertaining to meeting required flight schedules are used to assess operational risk associated with various support equipment inventories.

Figure 4 contains the model abstraction developed for this effort. Fundamental to this simulation model is the cycle of an aircraft mission, pre-flight inspection and potential maintenance actions. Each cycle starts with a flight schedule identifying the aircraft for each mission. For each sortie, we pair the first two available similar aircraft. If an aircraft waits over 30 minutes for a pairing, the mission is cancelled, otherwise the aircraft taxi and take-off to conduct their mission.

When an aircraft returns it either has failures or does not have failures. If the aircraft returns fine the aircraft is inspected, serviced with fuel and loaded with ammunition. This inspection process may actually uncover components requiring repair at which point the aircraft enters maintenance. Aircraft returning with failures are checked to determine the specific failures at which time the aircraft enters the maintenance process to rectify the failure. Failures have corresponding maintenance actions requiring support equipment which is requested from inventory by the maintenance process.

Maintenance is modeled sequentially, with shorter duration repair actions coming first. Maintenance commences when all required support equipment assets are available for the particular maintenance action. If a required piece of support equipment is unavailable, the aircraft maintenance action is delayed. Once all pending repairs are complete, the aircraft is serviced, loaded with munitions, and made available for flight scheduling. The percentage of time each piece of support equipment is in use determines the overall utilization of that equipment.

Three different notional footprint reduction strategies were examined and compared based on how well the deployed unit met its flying schedule. The first strategy does not deliver all support equipment in the initial stages of the deployment; maintenance is restricted. This option yielded too high a risk to flight operations. The second strategy brings a minimal set of support equipment items and then requests rapid delivery of missing support equipment when the missing item is needed. The third strategy consolidates multiple single function support equipment units into multi-function units. These multi-function units reduce inventory but may incur a loss of functionality. The multi-function units are denoted MAGE and two combined support items, already fielded, are denoted SAGE.

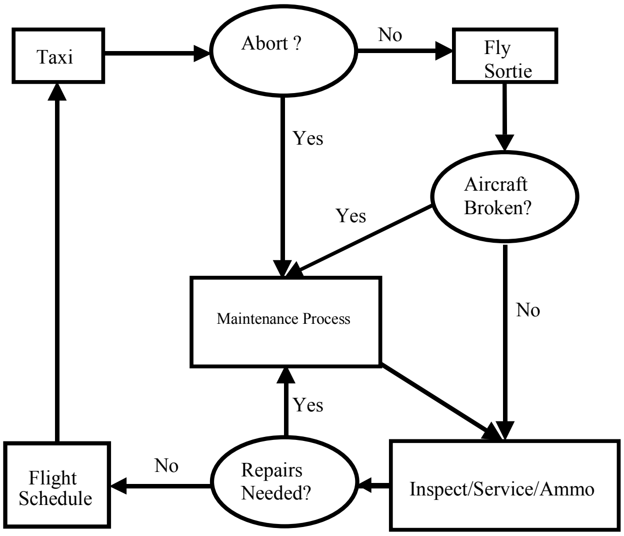

Figure 4: Model Logic for Inventory Reduction

A best-case scenario involving unlimited support equipment attained nearly a 94% schedule effectiveness. Not deploying equipment dropped effectiveness to the 50% range; half the scheduled mission do not occur which is of course unacceptable. Reducing inventories dropped effectiveness significantly, which makes sense. However, we found that a rapid delivery capability provided a means for the reduced deployment inventory to approach the effectiveness level of the unlimited support equipment scenario which is our upper bound.

5.3 Army Recruiting

The Army's recent recruiting problems are well known. In fiscal year 1999, the Army fell over 6,000 recruits short of its recruiting mission. As we enter the 21st century, the Army finds itself fighting to maintain force levels set by Congress.

The Army is determined to combat these recent recruiting problems. Over the past three years, the U.S. Army Recruiting Command (USAREC) has sponsored three research projects at the Air Force Institute of Technology (AFIT). The goal of each project was a better understanding of the workings of station-level Army recruiting. This paper briefly discusses each of these projects and is adapted from the most recent research (Longhorn, 2000).

In 1998, AFIT researchers James D. Cordeiro, Jr. and Mark A. Friend (Cordeiro and Friend, 1998) developed a station recruiting model based on extensive research from recruiting literature and recruiters in the field. They identified essential recruiting processes and interactions, which allowed for a detailed computer model implemented in the simulation language SIMPROCESS. The model simulated a single recruit type, also known as a prospect type. Prospects flow through the recruiting system, competing for the limited recruiter resources. Three recruiters, working independently, made up the recruiting station. Through simulation, Cordeiro and Friend (1998) discovered key factors influencing the performance of the simulated recruiting station.

McLarney (1999) enhanced the station recruiting model developed by Cordeiro and Friend. Significant enhancements included the incorporation of recruiter leadership and personality effects, along with allowing distinctions between different prospect types. McLarney (1999) gained further insights into the workings of station-level recruiting, but more importantly, sparked the interest in modeling the differences between prospect types – an important aspect of our research.

The most recent research (Longhorn, 2000]) resulted in a more flexible and accurate model of an Army recruiting station. The simulation models three recruiters of varying abilities, each capable of recruiting nine different prospect types. Analysis of historical recruiting data revealed recruiting seasonality in terms of recruits contracted and shipped to basic training during the year. We then incorporated these seasonality effects into the model, thereby providing recruiting analysts and decision-makers with a powerful analytic tool. We also established a methodology to approximate prospect input proportions into the recruiting system, an important feature adding accuracy and credibility to our model.

Simulation experiments provided valuable insights into the workings of Army recruiting. In particular, we discovered a highly sensitive recruiting factor - the recruiter's ability to "sell" the Army to potential recruits. This factor greatly influences the success of the recruiter and the performance of the station.

5.4 Modeling Strategic Effects

Airpower enables quick strikes against enemy targets, strikes whose effects yield catastrophic damage. Unfortunately, current Air Force fail to capture this inherent strength. We developed a simulation model, the Hierarchical Interactive Theater Model (HITM), using complex adaptive agent technology to investigate such strategic effects (Bullock, 2000).

We implemented Complex Adaptive Systems using agent-based modeling with individually adaptive decision making to allow agents to act autonomously. Agent interaction is governed by the agents not by the system. each agent adheres to Boyd's Observe, Orient, Decide, and Act Loop, or OODA Loop, modeling of command and control decision making. Each agent cycles through numerous OODA loops. The observe portion involves gathering intelligence information. The orient portion determines the value of information and how to use it in decision making. A best course of action is decided and implemented to complete the decide and act portions of the cycle.

Our agent-based model, where each agent has its own OODA Loop, provides a means to examine and gain insight into the nature of interactions and unpredictability in combat.

A HITM scenario involves two equally structured opponents with opposing objectives. Agents form the ranks at each level of the chains-of-command with actions to carry out in support of the overall objective. Agents react to enemy actions, friendly actions, and the environment. Each side has resources, which are considered targets by the adversary. Agents require the resources to carry out their actions, thus, destroying an adversary's resources slows down their ability to execute their strategy and the rate at which they can move through their OODA Loop. HITM endgame occurs when one opponent achieves its overall objective of capturing the adversary's airbase.

The battlespace in HITM consists of two equally sized areas arranged similarly; no side has an advantage. There are three primary resource groups or target sets: leadership/command and control, organic essentials, and infrastructure. The leadership/command and control targets represent intelligence gathering resources and communication links to include satellite down-links, radar sites, and telecommunications nodes. A strike against these targets degrades ability to gather intelligence and communicate. The organic essential targets represent sources of petroleum and other fuel products to include fuel storage depots, petroleum refining operations, as well as petroleum pipelines. A strike against these targets impacts rate of delivery and overall availability of fuel. The infrastructure targets include roads, bridges, and ammunition/weapon storage facilities. A strike against these targets impacts rate of delivery and overall availability of ammunition/weapons.

Experiments using HITM are conducted to study how two forces fare when pitted against one another. The experiment investigated two equally matched opponents. The goal of this experiment was to determine when and under what circumstances one side gained the advantage. Another important aspect examined is if a slight disadvantage for one side resulted in a brute force push to the objective or if it "snowballed" into total collapse.

Thirty runs were conducted under the equal fight scenario. Of those red won 17 times and blue won 13. No parameters were changed between simulation runs, however, there was wide variation of output among the simulation runs.

Czerwinski (1998) suggests all nonlinear systems can be characterized by three regions and links these regions to the battlefield. The first region is Equilibrium where damages inflicted by an opponent are local and their effects die out. The second region is Complexity. In this region, the damage inflicted by an opponent requires adaptation in order to overcome the effects. The third region is Chaos where damage inflicted by an opponent propagates and eventually results in destruction. These regions are prominent in the HITM output (Figure 5). Equilibrium is present at the start and is maintained for some time. However, if an opponent can not overcome the attacks, the opponent falls into the Complexity region and they become reactive to their opponent. If an opponent cannot adapt and push back into the equilibrium region, the effects of attacks propagate into eventual total collapse. Each boundary region was identified for each of the thirty runs. The Equilibrium to Complexity boundary was defined where the FLOT path becomes strictly decreasing with a point lower than any point in the equilibrium region. The Complexity to Chaos boundary was defined where the FLOT path slope becomes approximate -45 degrees.

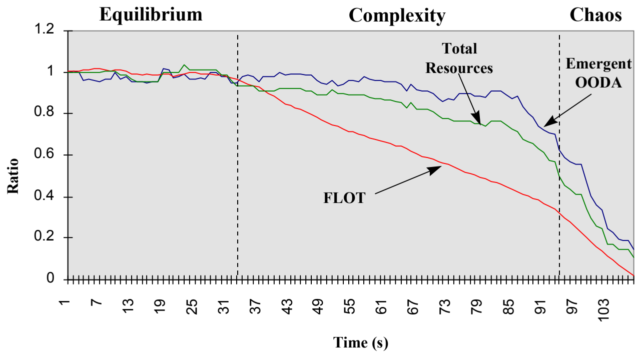

Figure 5: OODA Loop, Resources, FLOT Relationship to Regions of Nonlinear Systems

The importance of this experiment is that it demonstrates how an agent-based model allows one to model an unpredictable system while exploring transition periods within a military conflict.

6 SUMMARY AND CONCLUSIONS

The military is a BIG user of modeling, simulation and analysis. We are particularly dependent upon all forms of simulation, from live simulation, through virtual simulation to include virtual reality applications, and up to and particularly including constructive simulations. The more general purpose constructive simulation models in the AFSAT tend to be quite large and complex. This is the cost associated with a simulation containing many aspects of the military environment at a fairly detailed level of modeling. In the future, the military reliance and use of military constructive simulations will increase. With decreased money to expend, less time to prepare, and an increased need for combat effectiveness, the military needs every tool at its disposal to prepare for the future.

Disclaimer: *The views expressed in this article are those of the authors and do not reflect the official policy of the United States Air Force, Department of Defense, or the US Government.*

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