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USING AGENT-BASED MODELING TO CAPTURE AIRPOWER STRATEGIC EFFECTS

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ABSTRACT

Airpower's strength lies in quickly striking the enemy directly where they are vulnerable while being unhampered by geography and surface forces. Airpower theory suggests the effects of these strikes propagate throughout an opponent's military system yielding catastrophic output or strategic effects. Despite this theory being a cornerstone of US Air Force doctrine, current Air Force models do not seem to capture airpower's inherent strength. Since these models are used to support budgetary decision making, the US may not be funding the airpower capability it needs. This effort focuses on developing an approach to capture strategic effects in models. The approach establishes a basis for the effects in military theory as well as the field of Complex Adaptive Systems. Using these concepts as a foundation, a simulation model called the Hierarchical Interactive Theater Model (HITM) is constructed and exercised. HITM output depicts a cascading deterioration in force effectiveness and eventual total collapse resulting from destruction of vital targets. This outcome is consistent with the expected results of strikes against centers of gravity defined in Air Force doctrine suggesting agent-based modeling is an effective way to simulate strategic effects at the operational level of war.

1 INTRODUCTION

War is a clash of opposing wills that produces a dynamic interplay of action and reaction in which the enemy often acts or reacts unexpectedly (AFDD 1 1997). Interaction and unpredictability are timeless characteristics of warfare, however, the two are often discounted when modeling war.

Phenomena we do not understand are often ignored in models or in an effort to understand phenomena we "linearize" problems to derive an analytical solution. This linearization takes place by decomposing a problem into small, understandable pieces, deriving a solution for a single piece, and then multiplying by a factor to determine a solution for the whole. This partitioning process, however, comes at the price of realism since problems are not always decomposable into independent parts. The decomposition process fails to accurately capture the component interaction and these interactions dominate the real world making war unpredictable by analytical means (Beyerchen 1992). Carl von Clausewitz (1976) would agree stating:

> But in war, as in life generally, all parts of the whole are interconnected and thus the effects produced, however small their cause, must influence all subsequent military operations…

A model is only useful to the extent it yields trends and insights useful in making better decisions. So, how does one balance the need to capture war's realism, its interactions and unpredictability, and still provide decision makers with useful insight? The relatively new field of Complex Adaptive Systems may hold some answers.

2 COMPLEX ADAPTIVE SYSTEMS

A complex system is a set of elements that are interconnected so that changes in some elements, or their interrelations, produce changes in other parts of the system. In addition, the entire system exhibits properties and behaviors that are different from those of the individual parts (Jervis 1998). These systems are usually arranged in a hierarchical fashion with decentralized control, similar to a military chain-of-command. The adaptive portion means coping "at the time" by taking in external factors, building a new strategy, assembling ingredients to execute the strategy, and proceeding (Davis 1997). Combinations of these imply a system of elements where individual elements make their own decisions.

One approach to implementing Complex Adaptive Systems is through agent-based modeling. This modeling technique embeds decision models in system entities allowing for adaptive decision making (Palmore 1999). Adaptive decision making allows the individual entities, or agents, to act autonomously, governed only by an internal set of desires or drivers. Individual decision models also allow agent interaction to be governed by the agents themselves versus being governed by the system. A widely recognized decision model is Boyd's Observe, Orient, Decide, and Act Loop, or OODA Loop. The observe portion of the loop can be thought of as gathering intelligence information. The orient portion determines which information is of greatest value and how it is to be used in decision making. Based on the information, a decision on what to do is made and finally, selected actions are executed before the cycle starts again.

Watts (1996) suggests friction, or the dissipation of energy within an opponent's military system resulting from interactions, is an inherent feature of violent conflict. He further asserts that the balance of friction between two opponents can be manipulated to one's own advantage. Air strikes against centers of gravity are an example of how an opponent can induce friction on an adversary. Watts also suggests that "decision cycle times," or OODA Loops, can be used to gauge the friction on both sides of the conflict and the side with the lowest relative friction, and thus the quickest decision cycle, will have the advantage.

Interaction and unpredictability are often discounted when modeling war. An agent-based implementation of a Complex Adaptive System, where each agent has its own decision model, or OODA Loop, provides a methodology to examine and gain insight into the nature of these interactions and unpredictability.

3 MODEL DEVELOPMENT

Airpower strategic effects has its roots in the unpredictable interactions between the enemy, friendly forces, and the environment. A model specifically suited to examine these unpredictable interactions resulting from strikes against an opponent's vital targets, or centers of gravity, called the Hierarchical Interactive Theater Model (HITM) is constructed in a multithreaded JAVA program. Complex Adaptive Systems and agent-based methodologies form the theoretical framework for HITM.

HITM creates a scenario involving two equally matched opponents to include identical military chains-of-command, force structure, and force strength. However, the forces have opposed objectives. Autonomous agents, each with its OODA Loop, form the ranks at each level of the chains-of-command. Each agent has actions which it can carry out in support of the overall objective. Agents at each level react to enemy actions, friendly actions, and the environment. Each opponent 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.

3.1 Battlespace

The battlespace in HITM consists of two equally sized areas (Figure 1). The areas represent each opponent's territory. The entire battlespace is considered flat terrain, implying geography is not important. Each opponent's territory contains resources, or centers of gravity, representing war materials and processes. Both opponents have an equal amount of resources, all of which can be targeted by the adversary. The resources are positioned in a similar layout for each opponent, negating any geographic advantage.

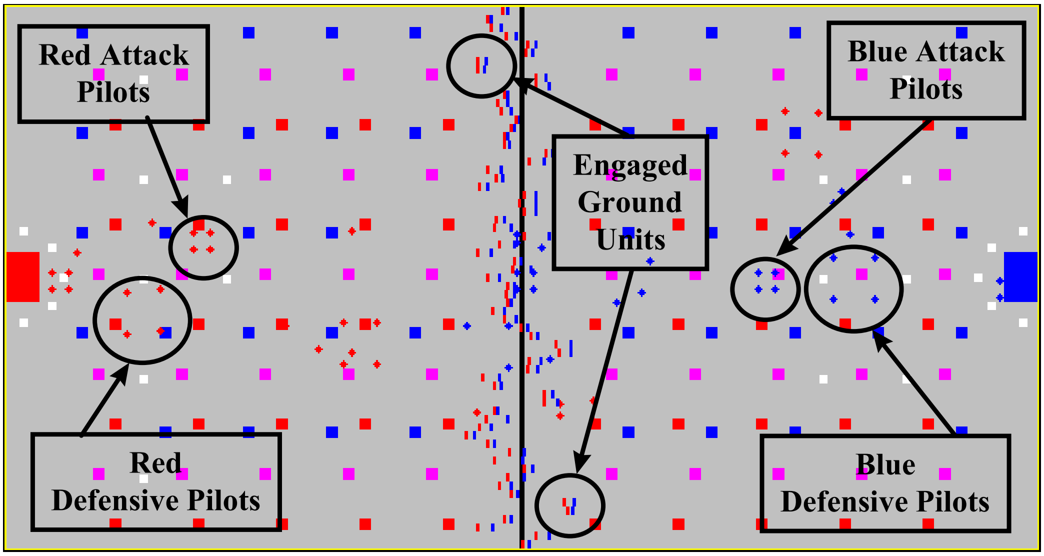


Figure 1: HITM Screen Shot

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.

The target sets are assumed to be highly redundant networks implying a single strike cannot eliminate a linkage between two points, but a single strike will cause degradation across the entire network. In addition, resources deeper in an opponents territory have more significance. For example, a single organic essential resource deep in an opponents territory contributes over 5% of fuel resources, however, an organic essential resource near the border between the two opponents, only represents 1%. The deep resources are also considered strategically more significant targets for the adversary.

Each opponent is limited to using 48 multipurpose aircraft at once. As aircraft are destroyed, HITM assumes additional aircraft resources can be obtained from other theaters. However, the rate at which these additional aircraft are delivered depends on the leadership/command and control resources available, as well as the total number of aircraft lost. Each opponent also has 65 ground units. The units represent elements of a single mechanized infantry division to include tanks, armored vehicles, and multiple launch rocket systems. However, ground forces do not have attack helicopters and rockets can only be used against aircraft during Close Air Support attacks. Unlike the aircraft, ground units are not replenished.

Each side has an airbase where aircraft are launched. The base cannot be completely destroyed, however, direct strikes against the base result in increased turnaround time for aircraft as airbase attacks represent strikes against runways and hangar facilities. Each side also has an Integrated Air Defense System (IADS). This system is composed of surface-to-air missile sites linked with radar facilities. The IADS is highly dependent on both leadership/command and control and infrastructure resources. The range of the IADS sensors are tied to leadership/command and control resources available and IADS probability of kill is linked to infrastructure resources available. The battlespace is modeled so the opponents are equally matched. Interaction between the agents tip the balance.

3.2 Agents

A key characteristic of Complex Adaptive System is a large number of non-homogeneous agents. In HITM, there are five classes of agents that make up each opponent's chain-of-command to include Commander, Operations, Ground Units, Defensive Aircraft Pilots, and Attack Aircraft Pilots. Agents within the same class have unique characteristics such as experience and unit cohesion, so no two agents are exactly alike. In addition, agents following the same decision path, may take different amounts of time to complete the same tasks. This is accomplished by running each agent as a separate thread of execution or mini-program.

All agents follow the same generic decision cycle, however, various agents take different amounts of time to complete their process. For example, the Commander's decision process is approximately 10 times that of the ground units at the start of the simulation. The decision process response time changes as the simulation progresses. Agents begin each decision cycle by observing. In the observe phase, the agents take in raw data, as well as direction/messages from other agents. In the next phase, orient, agents synthesize the raw data from the observe phase into information. Also during the orient phase, agents determine their available resources. Knowing the situation and the resources available, agents move into the decide phase. In this phase, the agents select from a number of alternatives based on the results of the orient phase. The final phase is act. In this phase, the agents execute their chosen alternative.

All agents continue to repeat their decision cycle until one opponent achieves its objective of capturing the other opponent's airbase. The speed at which an agent moves through its decision cycle is driven by internal factors such as unit cohesion and external factors such as resources available. As resources are destroyed by the adversary and become more scarce, decision cycle time degradation accelerates. HITM also incorporates battlespace uncertainty. The uncertainty is added by returning intelligence data to the agents that may be different from the actual values. In addition, the decision cycle delay incorporates the impact of acting on old information. These general details apply to all agents, however, each agent class has a unique OODA Loop.

3.2.1 Commander

The Commander's objective in HITM is to ensure proper coordination of ground and air efforts to attain the overall objective. The Commander's decision cycle begins with the observe phase. This phase involves the collection of intelligence such as data on the status of the ground war to include ground unit wins, Forward Line Of Troops (FLOT) location, and distance between enemy ground units. In addition, the intelligence includes information on friendly resources including aircraft lost. In the next phase, orient, the raw data is synthesized into information on which to base decisions. The time to collect and synthesize this information is a function of leadership/command and control resources available. In the next phase, decide, the Commander uses the information from the orient phase to make decisions related to aircraft apportionment and ground unit posture. In addition the Commander uses the information to determine target set priorities. Finally, in the act phase, the Commander communicates the decisions to the ground units and Operations.

3.2.2 Operations

The objective of Operations is to direct air efforts in support of the Commander's objective. Operations begins its decision cycle in the observe phase by receiving direction from the Commander concerning apportionment and target set priority. Also in this phase, Operations collects intelligence on the ground war, enemy targets, enemy air assets, friendly air assets, and resources available. In the next phase, orient, Operations synthesizes the data from the observe phase into information on which to base decisions. Operations uses the information from the orient phase to make the decisions in the next phase, decide, related to air defense and attack missions. Finally, in the last phase act, Operations executes chosen alternatives.

All aircraft are launched as 4-ship formations. The time to launch the 4-ship is a function of all resources available, the total number of friendly aircraft lost, and the number of successful airbase attacks carried out by the enemy. Operations is empowered to launch the defensive aircraft at anytime, however, the Commander has to send a target set priority before an attack aircraft can be launched.

3.2.3 Attack Aircraft Pilots

The objective of the attack aircraft pilot is to destroy targets, either ground forces or enemy resources, designated by Operations. Each pilot in HITM is unique. Each has a different experience level and a different level of will. These characteristics impact execution of the pilot's mission. The attack aircraft pilot decision process begins in the observe phase by collecting intelligence. For the attack aircraft pilot, this involves determining current position relative to the target for navigation. It also includes determining the number of friendly and enemy aircraft within sensor range. In the next phase, orient, the pilot determines if the ratio of detected enemy to friendly aircraft exceeds the pilot's will to continue the mission. If this condition is true, the pilot may choose to abort the mission in the decide phase. In the final phase, act, the pilot executes chosen alternatives.

When a mission is aborted the pilot navigates back to base. However, as long as the pilot does not abort the mission, the pilot continues to the target even if enemy aircraft are in sensor range. The attack pilot will only engage enemy aircraft if the enemy is within firing range. When the attack pilot engages an enemy aircraft, the probability of kill is based on pilot experience, level of communications, and ammunition. The HITM defensive aircraft pilots have similar characteristics.

3.2.4 Defensive Aircraft Pilots

The objective for the defensive aircraft pilot is to obtain/maintain air superiority in the airspace assigned by Operations. Similar to the attack aircraft pilots, each defensive aircraft pilot is unique, with a different experience and will level. The defensive aircraft pilot decision process begins in the observe phase with collecting intelligence. This involves determining current position relative to the target for navigation. It also includes assessing the number of friendly and enemy aircraft within sensor range. In the next phase, orient, the pilot determines if the ratio of detected enemy to friendly aircraft exceeds the pilot's will to continue. If this condition is true, the pilot can choose to abort the mission in the decide phase. In the final phase, act, the pilot executes chosen alternatives.

When a mission is aborted, the pilot navigates back to base. As long as the pilot does not abort the mission, the pilot continues to the next assigned way point. However, unlike the attack aircraft pilot, the defensive aircraft pilot will deviate from course to intercept any enemy aircraft within sensor range. When the defensive aircraft pilot engages an enemy aircraft, the probability of kill is based on pilot experience, level of communications, and ammunition. In addition, defensive aircraft pilots do not engage ground units.

3.2.5 Ground Units

The objective for each ground unit is to proceed towards the enemy airbase as directed by the Commander. As with the pilots, each ground unit is unique. Each unit has a level of unit cohesion that changes throughout the duration of the battle. The unit cohesion level impacts the unit's effective probability of kill as well as the unit's rate of movement.

Each unit's decision process begins in the observe phase by receiving direction from the Commander. Then, the ground units gather intelligence related to enemy and friendly ground unit locations. The ground units synthesize this data in the next phase, orient, for use in conducting operations. Also in the orient phase, the ground units assess available resources. Using the information from the orient phase, influenced by the

Commander's direction, the ground units move to the next phase, decide. The ground units can chose from among three alternatives. The ground units can attack, move towards the objective, or hold ground. The probability of kill for an attack is based on ammunition, communications, and unit cohesion.

4 COMPLEX ADAPTIVE SYSTEM OUTPUT

HITM is designed to investigate the unpredictable interactions resulting from strikes against an opponent's vital targets or centers of gravity. The investigation is carried out by using HITM in a series of experiments.

Experiments using HITM were conducted to study how two forces fare when pitted against one another. These experiments had a dual focus. The primary focus was to examine the simulation outcome and determine why it occurred, when the forces were equally matched. A secondary focus was to investigate initial conditions necessary to drive desired outcomes. Measures of performance related to resources available for each side and decision cycle times for each agent were collected at one second intervals for the duration of the simulation runs.

4.1 Equal Fight

The first experiment using HITM investigated two equally matched opponents. The two opponents started off with equal forces and resources. However, as the fight progressed, the balance was tipped and one side gained the advantage. 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.

4.1.1 Results and Analysis

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 with simulation runs lasting between 69 and 184 seconds (s) with a mean of 106s and standard deviation of 29s. The focus of the output analysis was to find information that not only applied equally to all thirty runs but provided insight into how a given side was able to achieve victory. Since the concern was not with who won but why they won, the winner was compared to the loser for all thirty cases regardless of which side actually won.

Czerwinski (1998) suggests all nonlinear systems can be characterized by three regions (Figure 2) 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.

The characterization of the regions Czerwinski (1998) describes are evident when watching the HITM simulation and are also evident in the HITM output (Figure 3). The first region, Equilibrium, evolves since both opponents start with equal capabilities. Even after the start, the Equilibrium phase is maintained since attacks made by either side seem to only have local effects which die out.

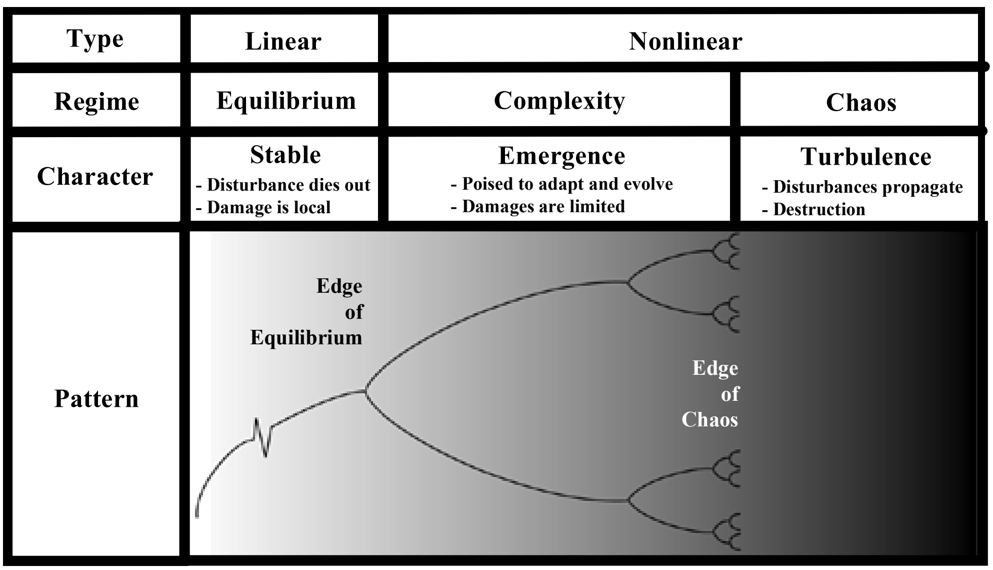


Figure 2: Characteristic Regions of a Nonlinear System (Czerwinski 1998)

However, if an opponent is not able to overcome the attacks, the opponent will fall into the Complexity region. Once in this region, an opponent is put in a position of reacting to the other opponent's actions. This region can be doubly damaging since resources are diverted from offensive to defensive operations. As shown in the Forward Line Of Troops (FLOT) path in Figure 3, if an opponent is not able to adapt and push back into the equilibrium region, the effects of attacks will propagate, eventually causing the opponent's total collapse. Using this common framework for all the simulation runs, the transition boundaries should highlight areas in the data indicating conditions necessary for one opponent to push another opponent into a nonlinear region and achieve victory.

Each of the boundary regions 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. The measures of performance were then collected at the boundary regions. The most robust indicators across all 30 runs were then identified by calculating the variance of the measures of performance and selecting the ones with the smallest variance. The identified indicators were total resources, which is the sum of the leadership/command and control, organic essentials, and infrastructure resources and the Emergent OODA Loop, which is the sum of all the agent's decision cycles. These indicators are plotted against the FLOT in Figure 3.

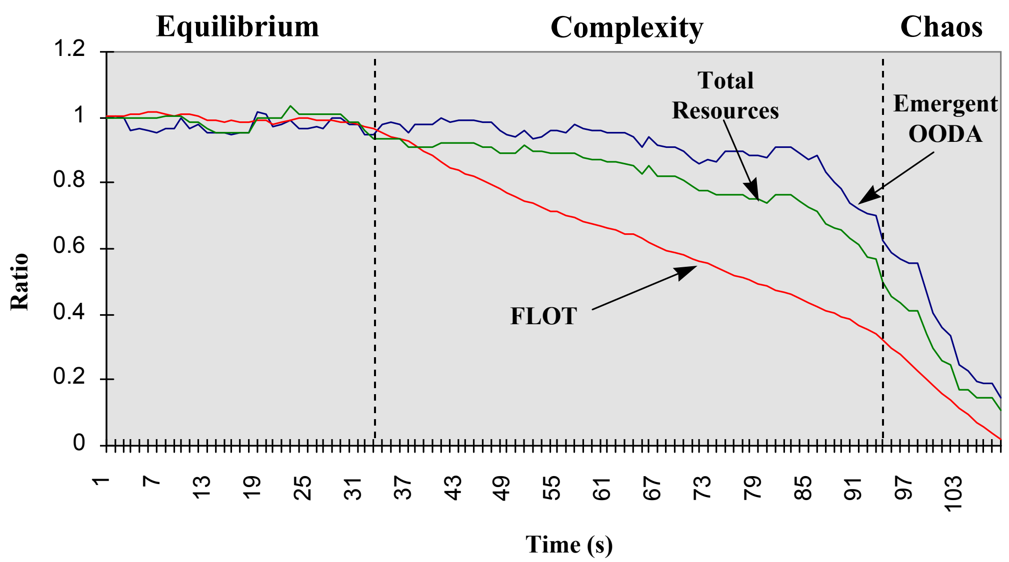
Figure 3 shows the relationship between the FLOT, which is the metric HITM uses to determine progress towards achieving the objective, the amount of total resources, and the agent decision cycle times. It depicts the cascading degradation of force effectiveness and total collapse resulting from destruction of an opponent's vital resources. Air Force doctrine predicts these same effects from air strikes against an opponent's centers of gravity.

4.2 Sensitivity to Initial Conditions

A model such as HITM can be used to determine which initial conditions have the most profound effect on a system which in turn could help identify centers of gravity. The second experiment investigated the impact of starting one opponent with various levels of degraded resources. The goal of this experiment was to determine the impact of the three resource types (Leadership/Command and Control, Organic Essentials, and Infrastructure) to determine HITM opponents' centers of gravity.

4.2.1 Results and Analysis

For each of the three resources the starting available amount for one opponent was varied at 87%, 80%, 73%, 67%, and 60% of the total available. The measure used for comparison was the time to achieve the objective (Figure 4). The figure provides insights between groups of resources as well as insights within a specific group. Comparing between the three groups of resources, one sees that no one resource is statistically different across the board. However, the infrastructure resources has elements that are statistically different from the rest. This implies infrastructure targets are strategically more significant than leadership/command and control and organic essential targets within the HITM battlespace. The importance of this experiment, however, is that it shows a an agent-based implementation of a Complex Adaptive System allows one to model an unpredictable system but at the same time allows one to explore which initial conditions drive robust solutions.



Figrue 3: OODA Loop, Resources, and Objective Relationship

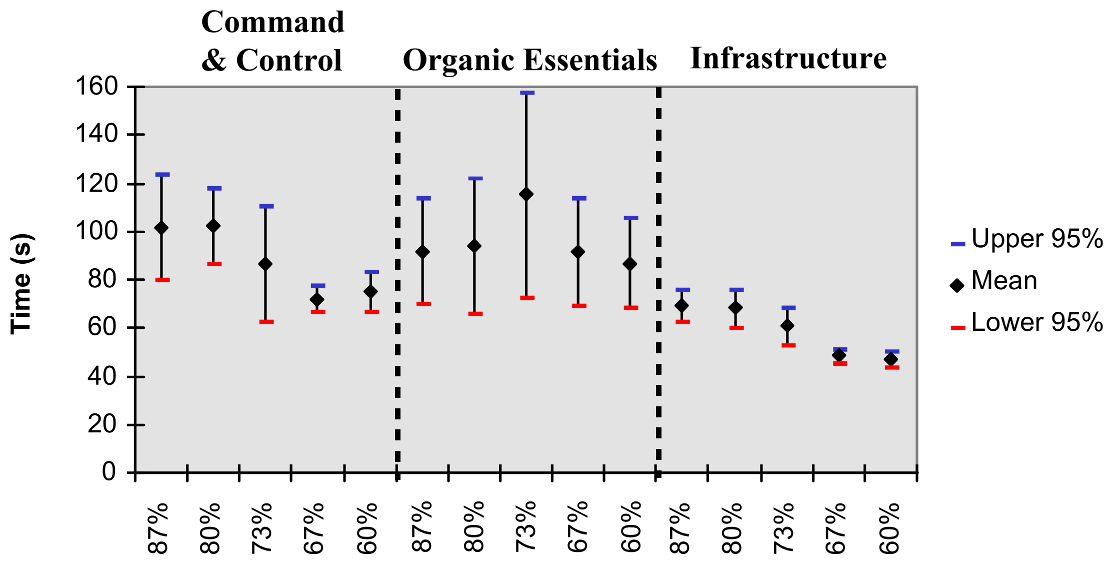


Figure 4: Time to Achieve Objective

5 CONCLUSION

The foundation of HITM is built upon classical military theory as well as concepts from Complex Adaptive Systems. The HITM experiment results depict a cascading deterioration in force effectiveness and eventual total collapse resulting from destruction of vital targets. This outcome is consistent with the expected results of strikes against centers of gravity defined in Air Force doctrine.

The purpose of exploratory models, such as HITM, is to assist in reasoning about systems, such as war, that contain significant uncertainty. HITM uses a bottom-up approach focusing on the actual processes of conducting military operations and the individual agents carrying out those processes versus an aggregated, top-down approach using theoretical, linear laws of combat such as Lanchester equations. The process oriented approach allows for capturing the interactions of the agents among themselves and interactions of the agents with the environment. This approach in turn allows for capturing friction, which slows down the rate at which an opponent can conduct military operations. Capturing the concept of friction is important because it is closely related to strategic effects. Air attack against vital targets, or centers of gravity, has the effect of interrupting or slowing the rate at which the enemy can conduct military operations, or in other words, air attack induces friction on the enemy.

The HITM experiments demonstrate how air strikes slow down the agent's process of gathering information, fuel, and ammunition. Even small slowdowns for each individual agent accumulates causing significant slowdowns at the organizational level. As the HITM experiments demonstrated, the key to victory lies in being able to operate inside the opponent's organizational level process or Emergent OODA Loop. In addition, analysis of HITM output suggests an agent-based modeling approach using OODA Loops is an effective way to simulate strategic effects at the operational level of war.

DISCLAIMER: The views expressed in this article are those of the authors and do not reflect the official policy or position of the United States Air Force, Department of Defense or U.S. government.

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