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SIMULATION OF TACTICAL DECISION MAKING BY WARFARE COMMANDERS[1]

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ABSTRACT

The *Tactical Decision Process* (TADEP) model described in this paper was designed to be used in conjunction with a series of man-in-the-loop simulation experiments to represent the information flow between the Anti-Air Warfare Commander (AAWC) and his operating environment. The TADEP model provides a dynamic tool for representing and assessing situational factors and human decision processes in relation to individual and organizational performance outcomes. The model can be used to compare different decision situations by varying the tactical characteristics of the battle, by changing the information flow, or by changing the characteristics of the decision maker and his decision processes. It can be used to evaluate the results of different decision strategies during all stages of an air defense from the outer-air battle through the transition to the inner-air battle.

PROBLEM

As part of a research and development program addressing design of future command, control, communications, computers, and intelligence (C^4I) systems, a method was needed for:

- summarizing relationships discovered in man-in-the-loop simulation experiments of command decision making in battle;
- operationalizing concepts and mechanisms that might be useful in clarifying understanding of the command decision-making process;
- testing potential alterations of variables to determine their impact on the command decision process.

This method would need to represent multiple factors that influence the decision process as it unfolds over time, and should be interactive, adjusting its representation of the situation to reflect actions taken by the decision maker. It was also important to minimize the cost (in both time and money) of tests and "experiments" on the decision-making process. These requirements describe a tool that could also be applied to gain insight into the larger problems of understanding technology-supported decision processes and designing improved decision support systems. No existing simulation tool was found that satisfied all these requirements (FSRAD 1989).

OBJECTIVES

The objective of this project was to provide a means for dynamically representing the factors and outcomes involved in command decision making in such a way that these complex phenomena could be better understood and alterations in the decision support system could be evaluated prior to experimental implementation with human subjects.

APPROACH

The *Tactical Decision Process* (TADEP) model described in this paper was designed to be used in conjunction with a series of man-in-the-loop simulation experiments to represent the information flow between the Anti-Air Warfare Commander and his operating environment (Kelly 1986; Callan, *et al.* 1990). The TADEP model can be used to compare different decision situations by varying the tactical characteristics of the battle, by changing the information flow, or by changing the characteristics of the decision maker and his decision processes (MORS 1989). It can be used to evaluate the results of different decision strategies during all stages of an air defense from the outer-air battle through the transition to the inner-air battle.

The TADEP AAWC is required to organize the data presented to him prior to making a decision. He is provided with a set of weapons and operational resources (example: aircraft, trackers, and flight operations controllers) that represent his assets and the organizational structures he can use to monitor and control those assets during tactical engagements.

The information flowing between the simulation objects in the TADEP model is a function of both the intrinsic nature of the objects and the decisions made by the AAWC on their utilization and deployment. Each simulation object carries default intrinsic capabilities: the default armaments, radar, and electronic devices available for an E-2 surveillance aircraft are different from those on a ship or an F-14 interceptor. These default capabilities can be modified so that a wide variety of tactical decision situations can be simulated.

The AAWC can launch aircraft, and can direct their use of weapons, radar, electronic listening (ESM), and interrogating (IFF) devices. Aircraft can be assigned stations to patrol or targets to cover. Once deployed, simulation objects operate independently to carry out their missions according to their intrinsic capabilities until they are recalled or redirected by the AAWC. Information obtained from deployed assets (e.g., aircraft, ships, or intelligence agents) is transmitted to the AAWC through communication channels, trackers, and other AAWC support mechanisms.

Choice of Modeling Tool

The TADEP model required a dynamic simulation modeling tool that was capable of representing the decision behaviors of the AAWC and the information flows that pass between him and his environment during an air battle. Eight development languages (ACSL™, "C", Design/CPN™, Extend™, Fortran, I Think!™, Micro-Saint™, and Stella™) were considered for this project. "C" and Fortran are general programming languages that allow complete control over a simulation but also require the user to program and develop the underlying simulation environment. Each simulation language provides a structure, data-flow primitives, plotting routines, and a standardized user interface for simulation. The Extend™ and ACSL™ simulation languages also permit user-definition of simulation modules and allow a programmer to code simulation objects in a variant of the "C" language (Extend™) or Fortran (ACSL™). These programmed objects can then be manipulated by the user in the same way as the other simulation primitives provided with the simulation language. The Extend™ modeling tools (Hoffman and Diamond 1990) were judged to provide a particularly useful combination of the advantages of the programming languages and the simulation languages since modules needed for the model could be designed and coded within the existent modeling structure, without additional development of code for the simulation environment.

Underlying Model Architecture

The TADEP model is designed to be a tool for representing the decision behavior of the AAWC in his normal working environment. To do this, it was necessary to design AAWC support modules that were sufficiently complex to generate the information used by the AAWC and which could respond to AAWC actions in ways that would influence the information that he receives during an engagement.

Although the TADEP modules themselves have familiar names (e.g., F-14A for some platforms), they do not attempt to reproduce all the behavior of the entities they model. They have appropriate platform capabilities[2] and will respond to AAWC commands and generate data for the AAWC to process, but they are not intended to replicate the internal structure of the systems they represent.

The TADEP model uses the object-oriented Extend™ simulation language to control the execution of the dynamic model. A set of code objects specific to the TADEP architecture was developed and incorporated in a library. That library can be accessed to deploy the forces used in each battle simulation. Basic modules in the TADEP library include Platforms (ships, aircraft, and their crews), organizational structures (Flight Operations and Communications), information sources (Trackers, Cryptography, Intelligence), information transfer and display (aircraft deployment lists, status boards), and AAWC functions (information selection, situation evaluation, response choice, launch and deploy-ment orders).

The AAWC module interacts with the Flight Operations, Platform, Tracker, and Communications modules during a TADEP model run. Information from these modules is selected and used by the AAWC module to update the AAWC's cognitive map of the external situation and the Blue battle group's status and deployment. This cognitive map is used in the decision strategies employed by the AAWC module. The AAWC module then produces launch, mission and deployment orders to the Blue platforms. AAWC orders pass through the Flight Operations module before they are transmitted to the platforms. This modularity and separation of the AAWC's decision functions from the collection and transmission of information allows evaluation of the effect of communication delays, information loss and degradation, and the characteristics of different command and control structures on AAWC performance.

A database of platform performance and avionics characteristics is provided to allow each basic platform to be configured as a particular aircraft or ship. Data are provided to allow the user to choose the (unclassified) performance characteristics and armaments for eight different platforms (F14A interceptor, F-18A interceptor, E-2 surveillance, KA-6 tanker, MIG-27 fighter, TU-16 bomber, Aegis cruiser, or commercial airbus). Provision is made both for user modification of the characteristics of individual platforms and for the use of a separate classified database of platform performance characteristics in place of the current, unclassified database. Separation between any classified and unclassified portions of the model allows program development and testing to be performed without access to classified performance data. Access to classified performance characteristics can thus be controlled and restricted to use in secure environments while model development and testing can be performed by using the same modeling code with an unclassified database.

The model architecture employs an object-oriented programming technique in which objects and their attributes form the modeling primitives. These primitives are arranged into classes and subclasses derived from the base objects. Sub-classes inherit the characteristics of their parents so that, as an example, a modified F-14A platform still possesses all the previous F-14A characteristics as well as the user-specified modifications. This object-oriented approach differs from models in which processes act upon data. It has the advantage of corresponding quite closely to the way in which experiments have shown that most commanders organize input data (into objects, their attributes, and their deployment).

Each module used in the simulation is coded as one of these objects. Organizational modules are provided to collect and distribute information to the warfare commander and to the units under his control.

The warfare commander himself is dynamically modeled. Since the TADEP model is based on a causal rather than a descriptive analysis of the AAWC decision environment, changes in the decision environment can be evaluated by determining their effects on the decisions made in the AAWC module. Alternatively, the AAWC module can be modified to evaluate the effect of different decision processes, strategies, or information delivery alternatives on the progression and outcome of the simulated engagements.

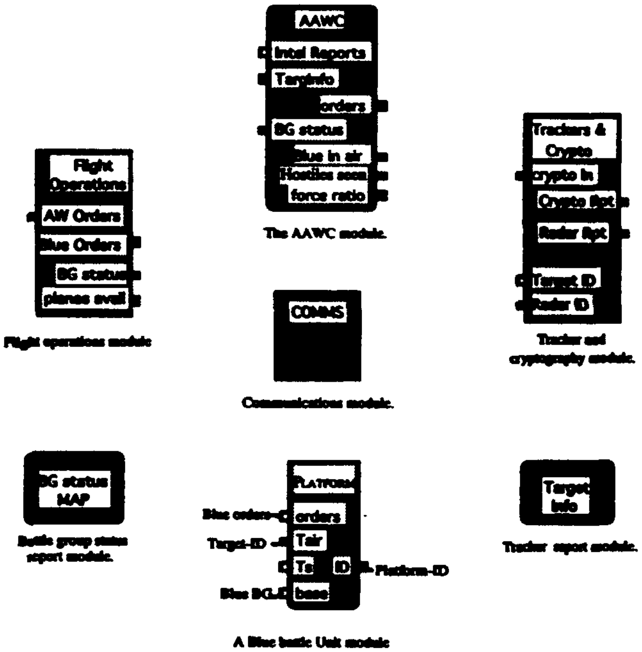
The decisions that the AAWC makes are based on the information presented to him and the way in which he integrates that information with his pre-existing mental map of the unfolding tactical situation. Just as in an actual engagement, the commander's actions can change the information that will be presented to him during the course of the simulation. For example, failure to position a unit within radar range of an incoming force will delay recognition of that force and can result in a temporarily low *perceived* hostile/friendly force ratio by the AAWC.

The dynamic modeling environment differs from an actual tactical situation in that it allows a single set of tactical conditions to be repeated multiple times while evaluating changes in AAWC decision and support alternatives. This control is not possible in either experimental, training, or actual tactical situations. In experiments the subjects may be influenced by previous testing to perform differently on subsequent experimental trials. In actual tactical situations the enemy cannot be expected to repeat his tactics to allow the AAWC to perfect a decision strategy.

The User Interface

The TADEP model is accessed through a user interface in which the user directly manipulates the objects used in the model. The interface is graphical, and allows modules from both the TADEP library and the Extend library to be selected, arranged, and connected in a window that shows an icon for each object in the simulation (Quinn and Fehér 1992b). Figure 3 shows the icons used to represent some of the modules that can be selected from the TADEP library.

Plotting modules can be placed in the simulation window and connected to any of the information sources. Each plotting module can graph up to four different signals and can be set to provide a real-time graph of what is happening in the model as a simulation unfolds. The scale and representation (color, pattern, etc.) of the individual items in each graph can be selected by the user. Data from the most recent simulation run can be viewed between simulation runs or stored in a data file by attaching data storage modules to the outputs of the plotting modules.



The AAWC module.

Flight operations module

Tracker and cryptography module.

Communications module.

Battle group status report module.

A Blue battle Unit module

Tracker report module.

Figure 1. Some TADEP simulation modules.

Figure 2 shows a plot of the actual number of incoming Orange aircraft (upper trace) and the number of incoming aircraft perceived by the AAWC (lower trace) plotted against time. These plots are displayed in color (orange and green respectively) during the simulation.

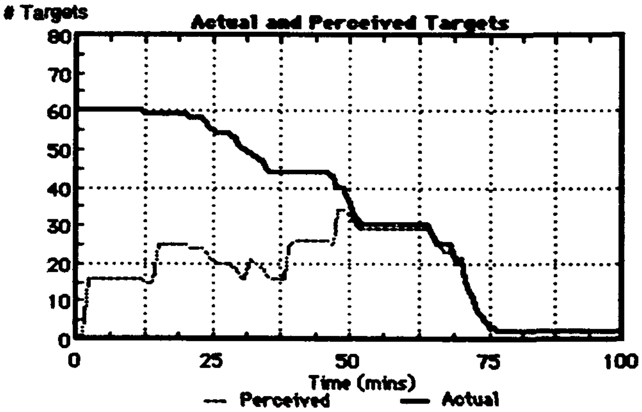


Figure 2. A plot of the actual number of incoming aircraft and those perceived by the AAWC.

The number of incoming (Orange) aircraft drops from 60 at the start of this model run, to zero as the AAWC successfully deploys his forces to engage the Orange forces. At 50 minutes all the incoming aircraft have been identified, and the AAWC's perception of the size of the hostile force matches the actual number. Other internal parameters can be plotted by using TADEP data extraction modules (not shown) to acquire data on internal AAWC and Orange PLATFORM parameters during the TADEP model run.

RESULTS

Model results were produced for two scenarios (Quinn and Fehér 1992a). In the first scenario four different launch decision strategies were evaluated against the same small incoming hostile force. The AAWC could influence the amount of information he received in this scenario by his decisions regarding deployment of his interceptors (F-14As) and surveillance (E-2) aircraft. Variables tested included use of intelligence information, E-2 launch timing, and interceptor launch criteria and launch delays. The simulation indicated that two of the four evaluated launch decision strategies could produce favorable results in the same tactical situation. One of these strategies utilized intelligence information about the armaments on the incoming aircraft. The other required early detection and identification of the incoming hostile force.

Simulation Results for Example 1

In this example identical initial conditions were used to evaluate the results of four different AAWC decision strategies that might account for the observed behavior of warfare commanders during the man-in-the-loop studies. In each case the Orange aircraft started from the same position with the same mission, weapons and destination. They continued on their mission (to sink the Blue ships) until they ran low on fuel and were forced to return to their base. The Orange platforms were set to operate without orders from the Orange AAWC and carried out their missions independently unless they were intercepted and prevented from reaching the Blue battle group's ships. Each TU-16 carried the standard complement of 1 air-to-surface missile and 3 air-to-air missiles and was set to operate with weapons "FREE" so that they would fire on any Blue units within range of their missiles. The Blue aircraft required orders from the AAWC before they could be deployed.

The intercept distances for two AAWCs, one "proactive" and the other sensitive to "force-ratio," are shown in Figure 3. Since the "proactive" commander has stationed his E-2 (not shown) within range of the incoming aircraft he is able to identify the incoming force much farther from the battle group than the other commander. His F-14s are launched earlier (upper plot) than those of the reactive commander, but they are shot down by the air-to-air missiles of the incoming aircraft. The remaining time between the engagement with the F-14s and the arrival of the enemy craft at the battle group allows the AAWC to issue his launch order for the F-18 fighters after the initial engagement and still destroy the incoming aircraft. The shaded track segment at the end of the incoming track shows the launch, engagement and return of the F-18s. This second engagement takes place over the battle group and, although successful, does not prevent some of the ships from being damaged during the battle. The F-18s are placed on station by the AAWC immediately above the blue battle group after the engagement (thin wavy line produced as the F-18s fly back and forth over the battle group).

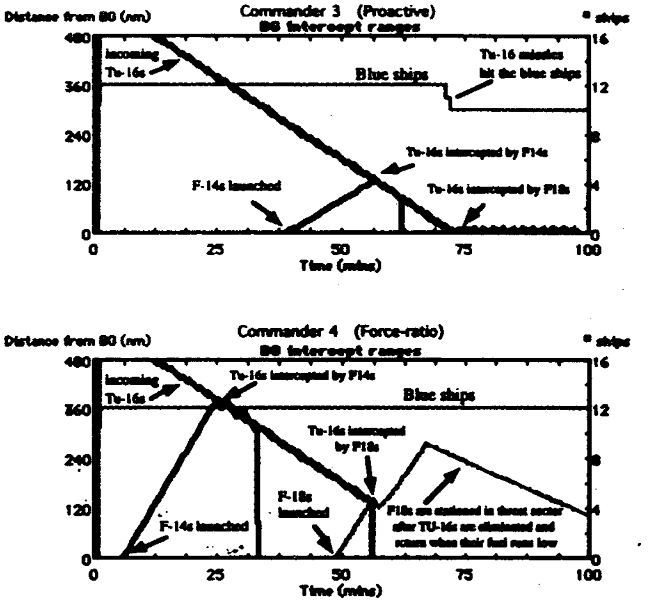


Figure 3. Intercept ranges for "proactive" and "force-ratio" commanders.

In the lower plot, the "force-ratio" commander attempts to keep a force ratio of one Blue interceptor for every two enemy aircraft. Since he is interested in keeping a favorable force ratio he launches his F-14s earlier than the previous commander. Although the outcome of the F-14 engagement is the same, the interception occurs farther from the battle group so that the F-18s (after a fifteen minute launch delay) are able to intercept and destroy the incoming aircraft before the incoming craft reach their weapon release range. The jagged thin line at minute 60 in the fourth plot shows the launch of the F-18s and their successful engagement as the number of incoming aircraft falls to zero. This commander chooses to keep the F-18s deployed within the threat sector after the engagement. They start to return to their base when their fuel runs low at minute 70 and are approaching the blue battle group at minute 100.

Simulation Results for Example 2

The second scenario involved larger complements of both hostile and friendly forces. It was used to explore the effect of differences in the information stream on commanders who attempted to maintain a particular force-ratio between hostile and friendly aircraft during a prolonged engagement. This simulation required exact specification of the launch delays experienced by each aircraft. It was particularly sensitive to differences between the force ratio perceived by the AAWC (his mental representation of the battle) and the actual force-ratio attained after launch delays and attrition had modified his deployment strategies.

Figure 4 graphs the force deployment and key outcome indices as the AAWC attempts to maintain a force ratio of four Orange aircraft for each Blue interceptor (4:1).

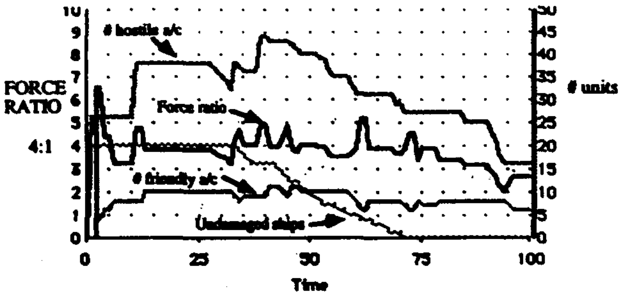


Figure 4. Indices and outcomes when the AAWC attempts to maintain a force ratio of 4:1.

A second simulation run (shown in Figure 5), demonstrates the results when the AAWC attempts to maintain a force ratio of 2:1. In each case the AAWC has launched Blue aircraft at appropriate times to maintain the desired force ratios in response to information on the number of incoming Orange aircraft from the **TRACKERS** and subject to delays produced by **FLIGHT OPERATIONS** in launching the Blue aircraft.

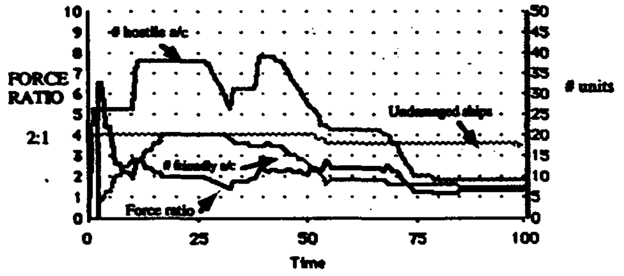


Figure 5. Results when the AAWC attempts to maintain a force ratio of 2:1.

The charts of these two battles look quite different because early decisions by the AAWC can change the battle and affect the information he receives for his subsequent decisions. This interdependence of AAWC decisions and the information he uses to make later decisions requires an interactive decision-effect model such as TADEP to simulate the AAWC decision process.

Comparing the two force ratio decision rules, we see that the 2:1 force ratio results in the expected higher peak number of Blue interceptors in the air than the 4:1 force ratio (20 vs 10), with the peak reached slightly later (17 minutes versus 13). The net effect of the stronger Blue defense is more rapid attrition of the Orange attackers, beginning at about 45 minutes. At the end of the 100 minute scenario, the Orange strength has fallen to 9 aircraft under the 2:1 force ratio versus 16 aircraft under the 4:1 force ratio.

DISCUSSION

The simulation results indicate that the TADEP model is capable of representing empirically observed AAWC decision processes and can reproduce scenarios from the man-in-the-loop simulation experiments that link AAWC decisions to the information available to the AAWC during battle.

The TADEP model was also able represent AAWC decision procedures and command and control structures in situations which were different from those for which the strategies were designed. This permitted the model to identify tactical situations in which a decision procedure might fail.

The simulated AAWC is required to organize the data presented to him prior to making a decision. This structure was dictated by the need to reproduce the observed behavior of AAWCs in man-in-the-loop simulation experiments and fleet exercises. The TADEP model separates an AAWC's decision rules from the objects that generate and transfer his input data. This separation allows data presentation techniques to change the way in which data are used by the AAWC and permits concepts such as mental maps and force ratio calculations to be examined in the model from a variety of cognitive and situational perspectives to determine where, and in what form, they might prove most useful. These determinations can be used to design better support by the C^4I system for these human decision processes.

TADEP simulations using this structure suggest that some differences in performance by commanders with similar training and experience may be due to differences in the mental models used by the commanders to organize their data. Application of the same decision rules to different internal representations of the input data was sufficient to produce markedly different performance by the simulated commanders.

Simulated commanders who successfully employed force-ratio calculations utilized mental models of the tactical situation that incorporated both launch and transit delays. Such a formulation is consistent with the man-in-the-loop simulation experimental data on AAWC performance.

The TADEP model is a critical component in cost-effective decision research methodology that provides both the capability to represent empirical man-in-the-loop behavior and the capacity to evaluate new mechanisms for decision support prior to man-in-the-loop testing (Fehér, 1990). Using the TADEP model, alternative decisionmaking strategies and support mechanisms can be tested to evaluate the relative magnitude of their impacts on overall outcomes. This would increase the efficiency of the man-in-the-loop studies by helping to eliminate less promising alternatives and allowing selection of alternatives that promise the most leverage over outcomes.

CONCLUSIONS

These examples indicate that the TADEP model is capable of representing some complex AAWC decision processes. Further, the TADEP model can reproduce scenarios from the man-in-the-loop simulation experiments and can link AAWC decisions and outcomes to the information given to the AAWC during battle.

The TADEP model can also simulate the use of AAWC decision procedures and command and control structures in situations which extend beyond those for which the procedures were designed. This permits the TADEP model to identify factors and variables in tactical situations which constrain or enhance decision performance. These capabilities make it a valuable tool to complement costly and time-consuming man-in-the-loop simulation experiments.

The separation in the TADEP model of AAWC decision rules from the objects that generate and organize his input data permits the effect of new data presentation techniques to be estimated by simulating the effect that these displays would have on the internal organization of data used by the AAWC to make his decisions.

The model suggests that performance of some commanders could be improved if decision support systems helped to perform some of the information processing functions of the more successful commanders. Data needed for the mental models used by the more successful commanders could be presented to all commanders to enable them to evaluate these techniques. TADEP simulations can be used to test the sensitivity of different AAWC decision processes to the presence and presentation of various kinds of information.

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BIOGRAPHIES

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[2] All platform performance capabilities are taken from *Jane's*.