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THESIS

THEATER LEVEL OPERATIONS OTHER THAN WAR MODELING: APPLICATIONS OF DECISION MAKING THEORY

By

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September 1994

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This paper presents an automated model for generating courses of action in support of an Operations Other Than War (OOTW) simulation. The model simulates the decision making of a theater level staff in the OOTW humanitarian assistance mission environment. The model uses probabilistic forecasting models and Bayesian techniques to predict what the state of a region in the theater will be some time in the future. Decision tree structures and the forecasting module are used to solve the decision making problem using expected utility. The model uses pairwise comparisons of utility attributes to obtain a decision maker's preference structure, This structure is applied over a multi-attribute utility function and the decision tree, to find the optimal course of action for some region of the theater at a specific time. Some variations on Lanchester's attrition equations are used to model attrition, the effect of civilians in a combat zone, and the effect of rules of engagement. The model was tested using data representative of Somalia in late 1992. The results indicated the best approach in this instance is to initially provide a high level of aid to reduce the civilian starvation rates then transition to a more aggressive posture with a strong force in readiness to retaliate for attacks by opposing forces.

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THEATER LEVEL OPERATIONS OTHER THAN WAR MODELING: APPLICATIONS OF DECISION MAKING THEORY

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Submitted in partial fulfillment
of the requirements for the degree

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ABSTRACT

This paper presents an automated model for generating courses of action in support of an Operations Other Than War (OOTW) simulation. The model simulates the decision making of a theater level staff in the OOTW humanitarian assistance mission environment. The model uses probabilistic forecasting models and Bayesian techniques to predict what the state of a region in the theater will be some time in the future. Decision tree structures and the forecasting module are used to solve the decision making problem using maximum expected utility. The model uses pairwise comparisons of utility attributes to obtain a decision maker's preference structure. This structure is applied over a multi-attribute utility function and the decision tree, to find the optimal course of action for some region of the theater at a specific time. Some variations on Lanchester's attrition equations are used to model attrition, the effect of civilians in a combat zone, and the effect of rules of engagement. The model was tested using data representative of Somalia in late 1992. The results indicated the best approach in this instance is to initially provide a high level of aid to reduce the civilian starvation rates then transition to a more aggressive posture with a strong force in readiness to retaliate for attacks by opposing forces.

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EXECUTIVE SUMMARY

Since the end of the Cold War the United States Armed Forces have been repeatedly called upon to perform operations that are not related to winning a full scale war. The frequency of U.S. involvement in these type operations, Operations Other Than War (OOTW), has increased at a rapid pace as the nation becomes more involved with United Nations operations world-wide. As a result, the development of appropriate decision logic to use in models for these types of operations is of interest to the U.S. Army.

In this environment, a decision maker must consider the impact of the planned operation on civilians, the public opinion in the U.S., and the host nation. In many instances the political and diplomatic factors outweigh the tactical and military considerations. The problem is to develop a model which will simulate the decision making process of a theater level staff in the OOTW environment. The model must consider as many of the OOTW specific factors as possible, while remaining computationally feasible. The model should be robust enough to handle a wide variety of situations and yet be simple enough to easily see the cause and effect relationships evident in the outcomes.

In order to capture some of the salient features of the OOTW environment, the decision making model uses existing decision theory and combat modeling algorithms and adapts them to suit the problem at hand. The forecasting module makes use of probabilistic forecasts to produce decision probabilities for use in a decision tree. The two forecasts are a threat forecast and a civilian aid requirements forecast. These forecasts use a Bayesian approach with a simple updating scheme to achieve a change in the posterior distribution of the decision probabilities. Another forecast is used to model intelligence gathered by sensors. These forecasts estimate the number of enemy forces, civilians, and the amount of foodstuffs a particular region of the theater contains. This induces some uncertainty in the decision module which allows the model to take into account the quality of intelligence data available to the decision maker.

The decision module uses a decision tree structure and multi-attribute utility theory to solve for the best course of action for a particular region of the theater at a specific time. The utility function form used is a logarithmic form with weights on each of the component functions. The component functions measure the utility gained based on the attributes of friendly casualties, enemy casualties, civilian casualties due to combat actions, civilian casualties due to lack of aid, and amount of aid delivered. A pairwise comparison of the attributes is performed by the decision maker which results in a least squares fit for the weights of the attributes. The weights are then used in concert with the component utility functions to form the additive compound utility function. The decision tree is then solved using a maximum expected utility criteria.

Lanchester's equations for the Square Law are used with attrition coefficients estimated using the Bonder-Farrell approach for combat actions involving civilians. Deitchman's Mixed Law is used to model any attacks by enemy forces against U.S. aid convoys when no civilians are present. To capture the effect of rules of engagement (restrictions in use of force to reduce civilian casualties) the attrition coefficients used when civilians are present are determined by the weight the decision maker places on civilian casualties due to combat. As the decision maker's weight for civilian casualties due to combat increases, the attrition coefficient for U.S. Forces decreases and the attrition coefficient for enemy forces increases. This models the effect of operating under increasingly stringent rules of engagement.

The decision model produces a course of action for each region in the theater for each decision cycle. However, there are typically not enough resources available to execute every course of action simultaneously. As a result, the final step in the decision model is to rank order the regional courses of action by utility value obtained. The courses of action are executed from the highest valued course of action toward the lowest until there are not enough resources available to execute the next course of action. Any unexecuted courses of action are deleted after the decision cycle is complete. The execution phase of the model takes the resources identified and applies them to the region specified and the resultant change in the world state is observed. This process continues until the theater goal is accomplished or the resources are exhausted. The model was tested using data representative of Somalia in late 1992.

I. INTRODUCTION

Since the end of the Cold War the United States Armed Forces have been repeatedly called upon to perform operations that are not related to winning a full scale war. The scope of these operations has ranged from humanitarian assistance, host nation assistance, hurricane relief, to protecting Kurds from attack following the Gulf War. The frequency of our involvement in these type operations has increased at a rapid pace as our nation becomes more involved with United Nations operations world-wide. From our current national security strategy, a continental based force projection structure, and our commitment to the humanitarian and peace missions throughout the world, we can expect a sizable amount of resources from the Department of Defense to be spent in these contingency type missions. As a result, the development of appropriate decision logic to use in models for these operations is of interest to the U.S. Army.

The objective of this thesis is to explore the field of decision making in an attempt to collect a useful set of tools from which to fashion a workable model. This model will be used to generate a series of sub-goals or courses of action in an attempt to attain a larger, theater level, goal. The environment that this model will operate in is the Operations Other Than War (OOTW) contingency operations environment. Specifically, an attempt will be made to apply the resultant model to the approximate situation in Somalia in early 1993. The model must formulate realistic goals within resource constraints and be capable of reacting to a changing world state. Every effort must be made to focus the effort of model development toward those aspects of OOTW that make these operations different than those of high intensity combat.

In Chapter II the background information required to understand the problem is discussed. The tools required to analyze combat missions are plentiful and well studied. However, the nature of operations other than war missions has forced the Armed Forces, in general, and the United States Army, in particular, to reexamine the way it analyzes these missions. The events in Somalia during Operation RESTORE HOPE have pointed out the need to review our analytic techniques and develop new models to examine the particular issues associated with operations other than war. The Future Theater Level Model has great potential for modeling these type operations.

In Chapter III the nature of the decision making problem in operations other than war is discussed. Decision making logic is the heart of any descriptive model of human behavior. It is through the process of making decisions that the effects of human thought and action can be seen, measured, and analyzed. The analysis of operations other than war missions has been overshadowed in the past by the requirement to study high intensity combat operations against the former Soviet Union. However, since the demise of the Soviet Union and the emergence of the United States as the last remaining superpower, the frequency and number of operations other than war missions has multiplied dramatically. The need to develop models to examine this previously little studied area has grown to become a concern for many key leaders in the U.S. Army. One of the most important elements of these models will be the embedded decision making logic that accurately represents the unique requirements of the operations other than war environment.

In Chapter IV pertinent research work done in preparation for solving the problem is reviewed. In all of man's written record there has been a preoccupation with conflict of interest. This preoccupation has become one of the dominant concerns for several academic areas: economics, sociology, political science, operations analysis, and others. This has led to the development of numerous approaches to modeling conflicts of interest among individuals and among institutions. We will restrict our study to those areas that are mathematically rigorous and computationally feasible. This restriction narrows the field of choices to several broad categories of thought:

- Decision Theory
- Game Theory
- Probabilistic Modeling
- Knowledge Based Systems

In Chapter V the construction and development of the model is discussed. In this chapter the tools and methods discussed in Chapter IV are reduced to those required to solve the problem. The focus of this portion of the thesis is to rigorously develop a mathematic representation of the model and generate source code to test the formulation.

In Chapter VI the results and conclusions are discussed. The sensitivity of the model to various input parameters is evaluated. In addition, the appropriateness of the results are discussed and analyzed. The final portion of this chapter is dedicated to a discussion of future work that could be done to improve the model.

This thesis attempts to formalize a model to use in a systemic simulation of military operations in an operations other than war environment. To the greatest extent possible the salient features of the operations other than war environment are captured and used in the formulation of the model.

II. BACKGROUND

Since the end of the Cold War the United States Armed Forces have been repeatedly called upon to perform operations that are not related to winning a full scale war. The scope of these operations has ranged from humanitarian assistance, host nation assistance, and hurricane relief to protecting Kurds from attack following the Gulf War. The frequency of our involvement in these types of operations, Operations Other Than War (OOTW), has increased at a rapid pace as our nation becomes more involved with United Nations operations world-wide. From our current national security strategy, a continental based, force projection structure, and our commitment to the humanitarian and peace missions throughout the world, we can expect a sizable amount of resources from the Department of Defense to be spent for these contingency type missions.

A. OPERATIONS OTHER THAN WAR

The tools required to analyze combat missions are plentiful and well studied. However, the nature of OOTW missions has forced the Armed Forces, in general, and the United States Army, in particular, to reexamine the way it analyzes these missions. The events in Somalia during Operation Restore Hope have pointed out the need to review our analytic techniques and develop new models to examine the particular issues associated with OOTW.

1. Environment

One of the major differences between standard combat operations and OOTW is the requirement to consider many diverse factors in the decision making process.

> Immediate solutions to difficult problems may not be obvious or may jeopardize long-term objectives. For example, certain military responses to civil disturbance may solve the immediate crisis but subvert the legitimacy of local authorities and cause further civil unrest. Humanitarian relief and nation assistance must not promote dependency on aid from outside sources. Quick, efficient action by U.S. Forces that resolve the immediate issue without considering the long-term consequences and goals may promote instability. In operations other than war, victory comes more subtly than in war [Ref. 1].

Operations in this environment can present a special leadership challenge since the activities of relatively small units can have operational and even strategic consequences. Commanders must be able to integrate activities of joint and combined forces as well as civilian and host nation agencies. The successful use of intelligence from a variety of sources, and an adept understanding of the regional and cultural orientations, can have an impact on the ability of our forces to achieve their goals. The integration of resources and efforts of a diverse group of forces and agencies to achieve our specific objectives are the keys to success.

OOTW will not always be peaceful operations. There may be certain factions that resort to fighting or other aggressive acts, in an attempt to defeat our purpose and advance their own. Our military forces have the intrinsic right to self defense, but the overwhelming use of combat power may complicate the process toward accomplishing our stated objectives. As a result, commanders must expect to conduct operations under restrictive rules of engagement.

The Army's presence and their ability to operate in austere environments may force them to become the de facto lead in operations normally conducted by other agencies. In this type environment, the commanders and staffs must be flexible and able to adapt to many ad hoc arrangements for success. Thus, the decision making process must take into account other factors not normally considered or only given a cursory examination in combat operations.

2. Imperatives

The imperatives of OOTW are derived from the principles of war that have guided the war fighting doctrine of the Army for many years. A summary of these principles is necessary as they guide the decision making logic used by commanders and their staffs to confront problems in the OOTW environment. These imperatives [Ref. 2] are the foundation for the proper frame of mind for decision making in OOTW.

a. Primacy of the Political and Diplomatic Instrument

In military OOTW, political and diplomatic objectives affect military decisions at every level from the strategic to the tactical. Commanders and their staffs must understand the specific political and/or diplomatic objectives and the resulting impact these objectives have on military operations. In most instances military operations will be in support of some political or diplomatic objective within the theater.

b. Unity of Effort

Unity of effort implies interagency integration and, when applicable, coordination with the host nation to achieve a common goal. The primary elements for unity of effort are common objectives, coordinated planning, and trust. Depending on the theater command structure and goals, the military staff may be the lead agency for planning and coordinating operations while in other instances the military staff may not be the lead agency. Military leaders must understand the impact their operational plans have on political, diplomatic, economic, and informational initiatives.

c. Adaptability

Adaptability is the willingness and skill to change or modify existing structures and methods, or to develop new structures and methods, to accomplish the mission. As the situation changes, military leaders must adapt through revising command and control structures and missions to the new situation. This requires careful mission analysis, intelligence preparation, and in many instances, regional expertise.

d. Legitimacy

Legitimacy is the willing acceptance by a people of the right of their government to govern, the willingness of a people to support a cause or policy, or the acceptance of a group or agency's right to make and enforce decisions. Legitimacy derives from the perception that authority is genuine, effective, and uses proper agencies for reasonable purposes. Appropriate use of the informational instrument of national power in concert with military operations can significantly enhance both domestic and international perceptions of the legitimacy of a given operation. No group or force can decree legitimacy for itself, but it can create and sustain legitimacy by its actions. Military leaders must be aware that their actions increase or diminish the perception of legitimacy which can aid or hinder the accomplishment of the mission.

e. Perseverance

Perseverance is the patient, resolute, and persistent pursuit of national goals and objectives for as long as necessary to achieve them. OOTW may not have a clear beginning or end, and may not be marked by decisive actions culminating in victory; however, this does not imply that decisive action cannot be taken. Military operations in this environment may involve protracted struggles. It is very important that the military commander gain and maintain the initiative to persevere in the accomplishment of the objective. Perseverance helps ensure that both civilian and military leaders reject limited short-term successes in favor of actions that support long-term goals.

f. Restricted Use of Force

Restricted use of force refers to the judicious, prudent, and thoughtful selection and employment of forces most suitable for the mission. Restricted use of force does not preclude the possibility of employing massive or overwhelming force, when appropriate, to display resolve and commitment. The rules of engagement (ROE) for military OOTW will usually be more restrictive, more detailed, and subject to more political scrutiny than those associated with any other type operations. As a result, these operations are often characterized by constraints on the weaponry, tactics, and level of violence. Rules of engagement formulated without regard to the impact of collateral casualties and damage on the ultimate objective may be counterproductive, may prolong the struggle, and may ultimately result in greater U.S. and hostile casualties than is necessary. Military commanders must be well versed in peacetime ROE, supplemental measures, request channels, and procedures for implementing them.

3. Relationships

Overall U.S. policies and strategies for OOTW are developed and coordinated by the National Security Council (NSC) through various interagency groups. These policies and strategies are promulgated through normal NSC structure to the various departments and agencies. Within the Department of Defense, the Secretary of Defense exercises overall supervision and oversight of military OOTW policy and resources.

The Chairman of the Joint Chiefs of Staff, as the principal military advisor to the President, Secretary of Defense, and National Security Council, provides advice on matters relating to OOTW. In addition, the Chairman is the channel through which directives from the National Command Authority are passed to the combatant commanders. The Chairman also develops and establishes joint doctrine and formulates policies for joint training and education concerning the military OOTW environment.

The combatant commanders are responsible, in coordination with the respective U.S. ambassadors, for the development and execution of military OOTW in their strategy and plans. They are the DOD focal points for operations and planning for military OOTW. It is imperative these commanders establish working relationships with the appropriate ambassadors, since planning for military OOTW usually involves the Department of State.

The political and dynamic nature of international relations poses organization and coordination challenges for the combatant commanders and their staffs that demand considerable flexibility and intellectual agility. The military instrument of national power will seldom, if ever, be in the lead, and direct application of U.S. combat capabilities is the least likely or preferred option. Instead, indirect application of U.S. military capabilities, through the Department of State's security assistance program will be the norm. The interagency environment that typifies the other than war operational setting requires the combatant commander and staff to integrate fully their efforts with those of other U.S. Government agencies.

The U.S. diplomatic mission to the host nation includes representatives of all U.S. departments and agencies present in the host country. Interagency efforts are coordinated among Country Team members and are subject to policy supervision and control by the Chief of the U.S. Diplomatic Mission, normally an Ambassador, who is responsible to the President for the conduct of U.S. in-country policy and personnel. This coordination process uses the Country Team concept to ensure all in-country activities best serve U.S interests. The Country Team facilitates coordination among the departments and agencies represented in the U.S. diplomatic mission

The Country Team's organization depends on the desires of the Chief of the Diplomatic Mission, the in-country situation, the agencies represented, and the character and scope of U.S. interests in the host nation or region. The configuration of the Country Team may vary from a large assembly with representatives from all the agencies in an embassy, to a specialized team made up of those directly concerned with the problem at hand, to a steering committee of a few members such as the Deputy Chief of the Diplomatic Mission, Defense Attaché, Agency for International Development representative, and the Chief, Security Assistance Organization (CSAO). Given the highly political nature of most other than war environments, Country Team coordination is generally extensive, often assuming the form of policy control. This coordination is intended to ensure unity of effort and eliminate counterproductive political and diplomatic, economic, informational, or military initiatives.

Although the combatant commander and the U.S. area military commander are not members of the diplomatic mission, they are usually represented on the Country Team. This representation may be accomplished by the appointment of the CSAO as the commander's in-country contact officer and/or by representation by a member of the commander's staff. The in-country security assistance organization may be designated as a Joint U.S. Military Advisory Group, Joint Military Group, U.S. Military Training Mission, Defense Field Office, or other title agreed upon by the host nation and diplomatic mission. In nations without such organizations, the Defense Attaché or a foreign service officer may perform the duties of contact officer.

The combatant commander's representative coordinates Country Team guidance and proposed military activities with appropriate agencies and military commands. Because the coordination process is based on the unique composition of each

Country Team, it follows no set pattern or style. The personality of the Chief of the Diplomatic Mission and the relationship with the combatant commander will obviously influence the dynamics of the coordination process. This coordination is accomplished with the combatant commander's staff which integrates both the theater planning and the Joint Staff strategic planning process. Required security assistance efforts are coordinated with the combat commander's staff and the Defense Security Assistance Agency. The contact officer also coordinates, as needed, with the Department of State and appropriate host nation agencies through the country team and the diplomatic mission. Assisting the combatant commander in the political coordination and communication process is the political advisor, a member of the Department of State permanently assigned to the combatant commander's staff.

4. Missions

There are a variety of OOTW missions that the armed forces may be called upon to perform [Ref. 2]. They include:

- Support to Insurgency and Counterinsurgency
- Combating Terrorism
- Peacekeeping Operations
- Support to Counterdrug Operations
- Contingency Operations

These missions have a wide array of military involvement and effort required. For the purposes of this study we will limit our exploration to Contingency Operations.

Contingency OOTW are undertaken in crisis avoidance or crisis management situations requiring the use of military forces to enforce diplomatic initiatives, respond to emergencies, or protect U.S. lives. These operations may take place throughout the operational continuum; however, they are most prevalent in the other than war environment. The situation is dynamic in a crisis, and the amount of available information grows virtually every hour based on intelligence reports. An adequate and feasible response in a crisis demands flexible procedures and requires rapid and effective communications and coordinated plans.

Contingency operations are likely to have a strong psychological impact on the attitudes and behaviors of the domestic and foreign populace. The capability of the world media to rapidly disseminate information increases the impact of the reaction at home and abroad. This impact must be considered when planning and conducting these operations.

5. Factors

A number of factors influence the nature and scope of contingency operations. These include the duration of the operation, the mobility and flexibility of available forces, available intelligence, overflight rights, country basing rights, available fueling assets, logistics support, communications support, psychological operations, civil affairs, public affairs, security requirements, and operational constraints. In many instances these operations are conducted in parts of the world with limited host nation resources, airfields, or port facilities. The factors most critical for our study are intelligence gathering, psychological operations, civil affairs, public affairs, security requirements, and operational constraints.

a. Intelligence Gathering

Intelligence gathering is a particularly critical part of contingency operations in an other than war environment. The rapid introduction of U.S. combat forces requires precise planning and information concerning the threat and mission area. Accurate, detailed, tailored, and timely all-source intelligence can greatly influence the success or failure of these operations.

Gathering intelligence in the OOTW environment is somewhat different from collecting combat intelligence. In OOTW, we are still concerned with the threat and the capability of the threat; however, we are also concerned with information concerning the political situation and civilian unrest. Intelligence analysts must gather a wider array of information from non-traditional sources to be effective in their mission. The Center for Low-Intensity Conflict developed a system to aid the intelligence analyst in evaluating this non-standard intelligence. This tool is the Low Intensity Conflict Instability Indicator Threat Matrix [Ref. 2 and 3]. The matrix contains over 500 indicators that instability exists and a method to help quantify the nature of the threat from that instability. The indicators cover a wide variety of intelligence data and are broken into subsets based on the type of mission for which the analyst is gathering intelligence. This matrix will help form the inputs to the intelligence fusion process in the completed model.

b. Psychological Operations

Psychological operations are important in OOTW contingency operations because they can help exploit hostile forces' vulnerabilities and can target audiences whose support is critical to success. Psychological operations are used to disseminate information to civilians and threat forces to turn their opinion toward supporting the U.S. initiate in theater. The information can take the form of print media, radio broadcasts, and television broadcasts. In essence, the effect of psychological operations is to help create the perception that the U.S. Forces and operations represent the best alternative to support, and that the threat is not worthy of support. In the model, we will use the psychological operations effects to alter other players' perceptions of U.S. Forces intentions.

c. Civil Affairs

Civil affairs elements foster a strong working relationship between the U.S. Forces in theater and the host nation government officials and U.S. Forces and U.S. Government agencies. They have a high level of regional and cultural skills, as well as professional and governmental expertise. The civil affairs elements' major role is to help foster a good relationship between the U.S. Forces and the political agencies in theater. The effect of this role is to create channels of communication, coordination, and support between the U.S. Forces and political agencies. This communication helps the combatant commander understand what is required from the political arm of national power and helps the host nation and U.S. Government agencies feel comfortable about the activities of the U.S. Forces. In the model, we will use the civil affairs effect to establish effective communication and coordination between the U.S. Forces and the political agencies in theater.

d. Public Affairs

Public affairs programs can provide accurate and timely information, consistent with operational security, regarding military operations to a worldwide audience. World opinion, to include the domestic U.S. audience, is often most influenced by initial media reports. The public affairs program is the interface between the media and the U.S. Forces. Good public affairs programs can enhance the deterrent effect of U.S. Forces by emphasizing our strength and resolve to use force as necessary. In addition, these programs can help build the perception among the world populace that the operations are proper and worth supporting. In the model, we will use the public affairs effect to improve or decrease the general populace support of U.S. operations in theater. The level of support is directly tied to the operational restrictions placed on the U.S. Forces commander.

e. Security Requirements

Operational security and deception are very important to the success of any operation. The impact of security requirements in OOTW is most often seen by the amount of force required to protect U.S. facilities and forces. In any contingency operation, we want to use the least amount of force to protect our assets, while maintaining a suitable level of security. The need to use the minimum amount of force comes from the perception that is created in the eyes of the host nation government and civilians. In the model, we will use the instability indications from the intelligence analyst and the level of support for U.S. operations by the general populace to determine the level of security required.

f. Operational Constraints

Operational constraints are frequently imposed on military forces in OOTW. The National Command Authorities (NCA) determine the criteria for U.S. Forces in peacetime. The mission, threat, as well as international law shape each operation. Host nation and other affected countries may impose constraints on force levels and deployments. These constraints most often take the form of restrictions on the force levels or types deployed, limits on the use of deadly force (Rules of Engagement), and restrictions on host nation facilities and air space use. In the model, we will use these constraints to limit the options available to the decision making logic at all levels. These constraints will most often be fixed at the start of the simulation but may be dynamic as the need arises.

6. Roles

Contingency operations can include a wide range of roles [Ref. 2] including:

- Disaster Relief
- Show of Force
- Noncombatant Evacuation Operations
- Recovery
- Attacks and Raids
- Freedom of Navigation and Protection of Shipping
- Operations to Restore Order
- Security Assistance Surges

Disaster relief operations are executed under the umbrella of humanitarian assistance and provide emergency relief to victims of natural and man-made disasters. Like humanitarian assistance, disaster relief operations are conducted across the full operational continuum. The U.S. military's participation in disaster relief has positive impacts for the U.S. government as well as the host nation and its populace. The military can provide the logistics support to move supplies to remote areas, extract or evacuate victims, provide emergency communications, conduct direct medical support operations, provide emergency repairs to vital facilities, and provide for civil relief and the maintenance of law and order pending re-establishment of control by indigenous police forces.

The development of appropriate decision modeling for contingency operations in an OOTW environment would dramatically aid in the understanding and analysis of these missions. For the development of this decision making logic, we will focus on one particular type of OOTW mission: disaster relief. The specific scenario we will use to develop and test this logic is Operation RESTORE HOPE, famine relief in Somalia.

B. SOMALIA SCENARIO

Somalia's recent history is characterized by political unrest that culminated in civil war and the ousting of the government, followed by clan warfare and a total breakdown in government functions. The background and other information pertaining to Somalia were largely taken from the U.S. Army report on Operation RESTORE HOPE, [Ref. 4].

Since the toppling of the government in January 1991, fifteen clans and sub-clans have vied for power, pitted against one another along tribal lines in a multifactional civil war. None of the clans has been successful in wresting control and the nation has drifted without a governing body for approximately two years. During this time the country's infrastructure has deteriorated, rendered useless by looters and the ravages of war. Before U.S. and UN intervention, organized government services, such as police, water, fire, and electric departments, at city and national levels ceased to exist. The ability to supply food to the starving citizenry was negligible or nonexistent. Somalia became an international "basket case", dependent on external aid to survive. Clan families, unable to resolve the power issues, resorted to obstructing movement of relief supplies and extorting money from relief agencies as an extension of the internal power struggle.

United Nations Operation in Somalia (UNOSOM) was established in April 1992 to provide a peacekeeping force to monitor a cease fire between the warring factions. By July 1992, fifty observers were in place, concurrent with the start of UN relief shipments. The U.S. began about the same time with Operation PROVIDE RELIEF by flying relief supplies for non-governmental organizations (NGO) to southern Somali from Kenya on U.S. military cargo planes. In August, the UN Security Council authorized the expansion of UNOSOM to four 750 man security units for the protection of humanitarian convoys and food distribution centers throughout Somalia. By late November, several nations had agreed to provide observers, security personnel, and logistics support forces. However, these early efforts proved largely ineffective as looting, extortion, and running battles between clans continued. Relief supplies were regularly diverted away from distribution centers by thieves.

It was against this backdrop that U.S. planning for the operation, Operation RESTORE HOPE, began in mid-November 1992. The operation was conceived as a four phased operation designed to secure the area for humanitarian relief efforts and then to turn over control of the security operation to the UN forces of UNOSOM. Phase I of the operation involved deploying U.S. Forces to Somalia to secure the port and airfield facilities of Mogadishu and Baledogle. Phase II involved expanding the security area to humanitarian assistance sites in Mogadishu and Baledogle. Phase III continued to expand the security area to outlying regions of southern Somalia. Finally, Phase IV was the hand-off of the security functions and responsibility to the UNOSOM forces.

The area of interest in Somalia is depicted in Figure 2.1. The modeling effort uses the area depicted in Figure 2.1 and the approximate deployment posture of the major clans as of late 1992. The civilian populace is modeled using rough measures of the populations for the major cities and regions in the area of operations. The terrain model for the study uses a node and arc network representation of the area of operations. The detailed description of the area of operations network can be found at Appendix A.

The forces considered for this study are limited to aggregations of the somewhat homogenous groups. The groups are explicitly modeled in the study as a separate and distinct side. The sides are Aideed Supporters, Aideed Clan, Neutrals, and U.S. Forces. The initial disposition of the forces for the scenario can be found at Appendix B. The initial conditions for the study are now set with terrain and deployed forces. There are certain restrictions and assumptions needed to fully establish the initial conditions required to properly represent the environment within Somalia in late 1992.

As an aid to evaluating the decision making logic we will use the framework of an existing research model known as the Future Theater Level Model (FTLM). This model architecture is fully discussed by Schmidt [Ref. 5] where he applies the model to a strictly combat scenario in Korea. Here the model will be applied to OOTW in Somalia.

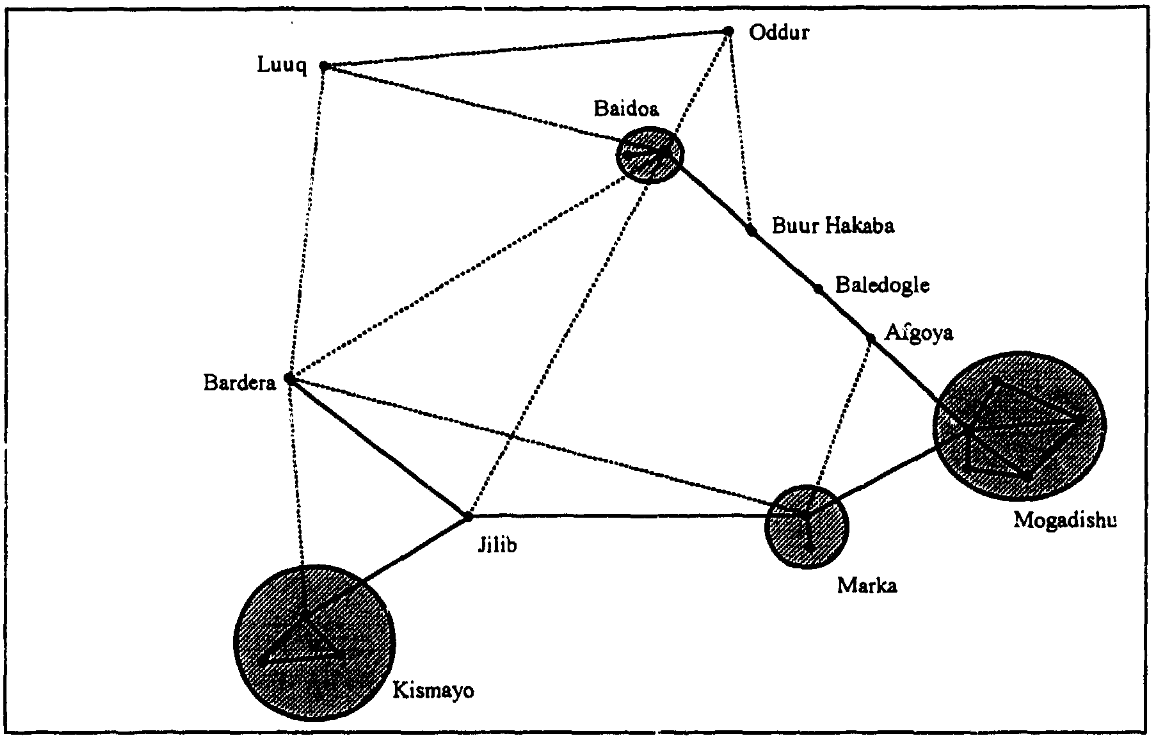

Figure 2.1. Southern Somalia

C. FUTURE THEATER LEVEL MODEL

Future Theater Level Model is a flexible model architecture under development at the Naval Postgraduate School. The model uses a network representation of the terrain consisting of nodes to model specific regions on the ground and arcs to model the mobility corridors that connect the nodes. The model contains an air grid to model the airspace over the network. The air model is capable of representing both rotary and fixed wing missions. The air model incorporates a mission planner that selects the target for each flight of aircraft from a list of potential targets and then develops a flight profile for that mission that minimizes perceived threat from enemy air defenses. The model is unique in its use of sensors to develop perceptions of the battlefield that can then be used by the simulation in the decision making process. The sensor model uses Bayesian updates to build a posterior distribution for the configuration of enemy units at specific locations on the network. This module is under revision to incorporate additional information concerning unit movements and formations as well.

The model for OOTW derived from the FTLM architecture is called the OOTW Theater Level Model, OOTW-TLM. This model, OOTW-TLM, is capable of multi-sided play. The number of sides is limited to a maximum of four at this time. Within each side there may be an unlimited number of factions. In the Somalia scenario a side would be analogous to UN Forces and the factions could be U.S. Forces, Canadian Forces, and Pakistani Forces. The sides have attributes, such as the hostility index, that describe the interaction among the sides (e.g. side A may dislike side B but like side C). These attributes are limited only by the imagination and ingenuity of the model developer. Within the context of the simulation, the sides maintain perceptions and can share perception information with other sides.

This model will eventually be used to study the decision making model formulation. This will be accomplished by incorporating the logic into the existing model framework and evaluating its performance. However, due to the current transition of the FTLM model architecture from a C++ coded personal computer platform to a SIMSCRIPT coded UNIX platform, the decision model will be tested independent of OOTW-TLM for this study. After the transition is completed, the decision logic will be incorporated into OOTW-TLM for testing. The construction of the existing model architecture is especially well suited to the OOTW environment because of the use of perceptions and the non-linear representation of terrain.

III. NATURE OF THE PROBLEM

Decision making logic is the heart of any descriptive model of human behavior. It is through the process of making decisions that the effects of human thought and action can be seen, measured, and analyzed. The analysis of operations other than war missions has been overshadowed in the past by the requirement to study high intensity combat operations against the former Soviet Union. However, since the demise of the Soviet Union and the emergence of the United States as the last remaining superpower, the frequency and number of operations other than war missions has multiplied dramatically. As President Clinton said during his commencement speech at West Point on 29 May 1993, "You will be called upon in many ways in this new era to keep the peace, to relieve the suffering, to help teach officers from new democracies in the ways of a democratic army, and still . . . to win our wars." [Ref. 6]. The need to develop models to examine this previously little studied area has grown to become a concern for many key leaders in the U.S. Army. One of the most important elements of these models will be the embedded decision making logic that accurately represents the unique requirements of the operations other than war environment.

In operations other than war missions, as in any military operations, there is a hierarchy of command and control relationships that define the decision making structure. In the case of operations other than war there is the added dimension of a networked coordination and control structure at the theater level. Figure 3.1 depicts the structure of the usual decision making process in the operations other than war environment. The networked decision structure is clearly visible at the Theater level of the diagram. This networked structure, combined with the unusual factors for decision making, are what makes decision making in operations other than war different from decision making in standard combat operations. From the figure, the levels of decision making are fairly easy to identify. These levels are the Strategic, the Operational, and the Tactical. The Strategic level corresponds to the National Command Authority and United Nations level decision making. At this level the goals and objectives for the operation are formulated, as well as the restrictions that are binding in theater. The Theater level corresponds to the decisions made in the theater of operations based on higher level (Strategic) guidance and directives. This level includes frequent coordination and control among the various

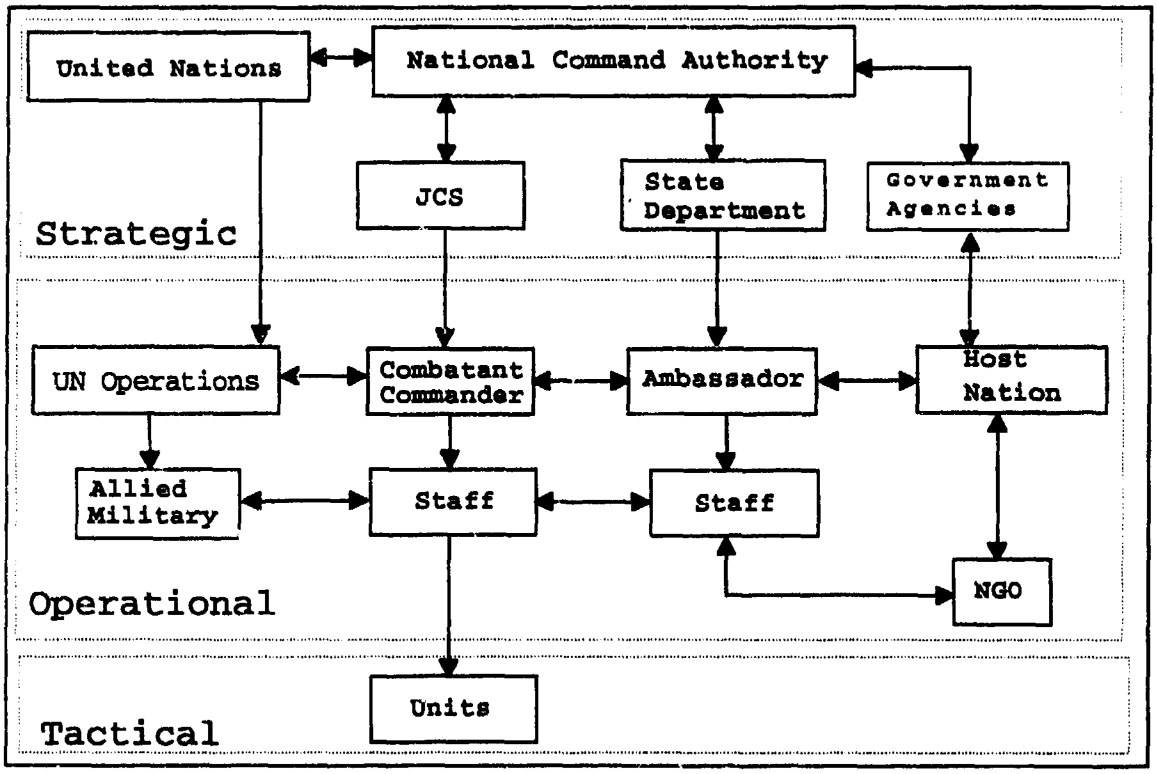

Figure 3.1. Decision Making Structure

agencies and the host nation. The lowest level is the Tactical level where units respond to guidance and directives from the Theater level. Tactical level decision making is primarily focused on unit responses to specific situations. This is analogous to action on contact drills used by many units in the U.S. Army.

For this study the Strategic level of decision making will be considered fixed at the start of the simulation. Thus, the restrictions and goals for the theater are known inputs to the model. The areas of decision making we will focus on are the Theater and Tactical levels. The primary focus at the Theater level is to determine the priority of effort to achieve the strategic goal subject to the restrictions placed on the agencies by the Strategic level decision makers. Once the priority of effort is determined, the next most important decision is how to allocate available resources against the prioritized efforts. Thus, the problem can be decomposed into two stages: prioritization of missions to accomplish the strategic goal and then a resource allocation stage where resources are partitioned to accomplish the missions. Once the final stage is completed, the units execute the plan and information concerning the success, failure, or problems encountered is reported back to the tasking agency. On the basis of this new information and additional information provided by other agencies, the mission prioritization and resource allocation begin anew.

A. MISSION PRIORITIZATION

The wide variety of agencies active at the theater level creates a chaotic decision making environment. These agencies have their own agenda and perception of what is the most important mission to be accomplished at any time. To complicate the decision making process further, these agencies are not in a hierarchical structure but are networked. Within the network structure there are some links between agencies that are formalized, such as the combatant commander and the ambassador, and others that are formed as a matter of convenience to the agencies, such as the non-governmental agencies and the ambassador. In this environment, the agencies must employ a wide variety of behaviors in an attempt to further their point of view (perception). These behaviors can take the form of coercion, negotiation, bargaining, and friendly cooperation. Thus, a major problem is how to deconflict the competing mission priorities of various agencies and form a short and long range plan to attain the strategic goal.

B. RESOURCE ALLOCATION

Allocation of resources toward specific missions is not a simple proposition in the operations other than war environment. Once the agencies determine a prioritization of missions, there is no requirement to provide the resources to execute this strategy. In this environment, each agency usually controls some specific resource that is important to the success of the mission but not readily available to the other agencies. For example, the U.S. military controls the resources to provide security for convoys and feeding sites; the

Red Cross and U.S. Aid, two non-governmental agencies, control the vehicles, food items, and feeding sites necessary for humanitarian assistance; and the host nation is sovereign over its roads and terrain. Thus, all three agencies control a key portion of the resources required to feed the starving populace effectively. By bringing these resources together, the mission (feeding the starving people) can be most effectively conducted. However, there is no requirement for the Red Cross or U.S. Aid to cooperate with the military. They could hire local militia to protect their assets and then attempt to feed the starving people.

In this case, the problem becomes more complex because specific resources can combine in certain ways to produce the most desirable outcome, yet other combinations of resources can combine to accomplish the same mission but at a lower level of satisfaction. Thus, a major portion of the problem is how to combine the resources of various agencies to achieve specific missions and then to measure the effectiveness of these combinations.

C. KNOWLEDGE FUSION

The collection of information from a variety of sources is very important to the decision making process at the theater level. Each agency has its own sources of information that helps to build its perception of the current state of the theater. Based on this perception, the agencies form opinions as to the most desirable prioritization of missions and their expectation of the effects of accomplishing these missions. The diverse data feeders in this environment range from reports by civilians to aid workers to satellite data from military intelligence sources. Each agency has at its disposal some subset of this spectrum of data collection. This diversity causes one of the first problems in building a perception for each agency -- how to integrate a wide variety of information sources into a vector to describe the current world state as perceived by the agency.

Each agency determines what portion of the information it collects will be made available to others and what portion will remain unshared. Besides the problem of fusing the data into a state vector, we have the additional problem of parsing information into categories by each agency. The separation of data by an agency may be specified by type of information and which agency to allow access to that type information. As a result, agencies can use their own knowledge of the state vector to influence other agencies' perceptions of the world state. This issue further defines the problem of knowledge fusion into how to form a perception of the state vector and use this perception to influence other agencies' decision making processes.

D. UNIT DECISIONS

The tactical level of decision making in the operations other than war environment is an important portion of the decision making structure. Actions by small units can significantly affect the perceptions of the host nation, U.S. citizens, and the world. The decisions of a unit when faced with a lage mob of civilians, an armed band of militia, or other hazards has far ranging impacts beyond the immediate effects of casualties or mission failure. Thus, the problem is how to model the decision making process of small units when faced with certain problems and how to propagate the effects of these decisions throughout the model.

E. CONCLUSION

The problem of modeling decision making in the operations other than war environment can be viewed as a three level process. The decision levels are composed of the Strategic (known inputs to the model), Theater (mission planning and coordination), and Tactical (actions on contact). We will focus on the Theater and Tactical levels of decision making for this study. In the Theater level of decision making the problem can be broken into three issues.

- How to prioritize missions among the conflicting demands of agencies.
- How to allocate resources from these agencies.
- How to build and use an agency's perception of the world state in the decision making process.

IV. REVIEW OF LITERATURE

According to Luce & Raiffa [Ref. 7], in all of man's written record there has been a preoccupation with conflict of interest. This preoccupation has become one of the dominant concerns for several academic areas: economics, sociology, political science, operations analysis, and others. This has led to the development of numerous approaches to modeling conflicts of interest among individuals and among institutions. We will restrict our study to those areas which are mathematically rigorous and computationally feasible. This restriction narrows the field of choices to several broad categories of thought in this area:

- Decision Theory
- Game Theory
- Probabilistic Modeling
- Knowledge Based Systems

Each of these will be thoroughly examined in the following sections.

Luce & Raiffa [Ref. 7] divide the field of decision making according to whether a decision is made by an individual or a group and then whether it is effected under conditions of certainty, risk, or uncertainty. They argue that the division of the field by individual and group decision making is not a biological-social distinction but a functional one. Thus, an industrial organization can be considered an individual in competition with other similar organizations or as a group composed of competing departments. They define decision making under certainty, risk, and uncertainty as follows:

Certainty if each action is known to lead invariably to a specific outcome. *Risk* if each action lead to one of a set of possible and specific outcomes, each occurring with a known probability. The probabilities are assumed to be known by the decision maker. *Uncertainty* if either action or both has as its consequence a set of possible specific outcomes, but where the probabilities of these outcomes are completely unknown or are not even meaningful [Ref. 7: p. 13].

From these classifications, they show that utility theory is concerned with individual decision making under risk. They then argue that conflicts of interest are ideally a problem of individual decision making under a mixture of uncertainty and risk, uncertainty arising from the ignorance of what the others will do. They propose game theory as a means by which the idealization of the problem reduces it to one of individual decision making under risk.

The idea of uncertainty in decision making lead to the development of statistical methods for making decisions even when the state of the world is unknown. This lead to the development of probabilistic models of decision making. The most notable model in this field is Baysian inference. Pearl [Ref. 8] explains the foundations of Baysian methods and develops these techniques for use in decision making problems.

The problem of group decision making is concerned with the complex interactions of preference patterns among individuals and how to amalgamate these patterns into a composite pattern for the group. Bartos [Ref. 9] uses the concept of dominance relationships in conjunction with a mix of Markov chains and game theory to tackle this thorny problem.

The final area of interest is used to model the group interaction process as well as the cognitive problem solving processes of humans. This field is knowledge based or expert systems which uses artificial intelligence solution techniques to create a model of the human decision making process. Several approaches will be examined including applying uncertainty measures to knowledge and inferences from that knowledge and using distributed agents to negotiate the solution to a problem.

A. DECISION THEORY

The major premise behind decision theory is that people have certain preferences among various rewards. We can view a decision as a tree, where at each fork we must decide which path to follow, and if we can predict the outcome for following a certain path, we can project the preference function over the outcomes and choose the preferred outcome. In most cases the reward is known as utility that is gained from choosing a specific path through the decision making process. Utility is most often measured in dollars or some other universally transferable commodity. The concept of utility underlies a large portion of the research in this and most subsequent fields.

In their discussion of decision theory, Luce & Raiffa [Ref. 7] develop the underlying concepts of utility theory and argue for the principle that people behave according to an expected value process. The concepts are based on the notion that decisions are like gambles where any one of n outcomes are possible, each outcome is worth $a_1, a_2, \ldots, a_n$ dollars, respectively, and the probabilities of these outcomes are $p_1, p_2, \ldots, p_n$. Then, as shown in Equation 4.1, the monetary expected value of the gamble, b, is

$$b = a_1p_1 + a_2p_2 + \ldots + a_np_n \tag{4.1}$$

and the fair price for the gamble is the expected value, b. However, this simplistic approach is shown to be flawed by explaining the St. Petersburg paradox of D. Bernoulli. The paradox is the proposition of a gamble where a fair coin is tossed until a head appears. The gambler is then paid 2^n dollars if the first head appears on toss n. Based on the aforementioned expected value argument, the gambler should be willing to pay an infinite sum to participate in this gamble since the expected value is infinite. This does not make good common sense. They then propose the solution offered by Bernoulli that people behave according to the expected intrinsic worth of the gamble. The major point here is that people behave according to an expected value of utility gained rather than according to the monetary value of the gamble.

Luce & Raiffa then propose the von Neumann and Morgenstern approach to developing the utility function for an individual. The assumption made is that if a person can express preferences between every possible pair of gambles, where the gambles are taken over some basic set of alternatives, then he can introduce utility associations to the basic alternatives in such a manner that, if he acts according to expected utility, he is acting according to his own tastes. This assumes his tastes are consistent. Another way to state this is that the preference relations are transitive. Luce & Raiffa then enumerate the six axioms that must be satisfied to form the utility function. The most important of these is that the preference relationships must be transitive; any gamble must be decomposed into its basic alternatives according to the rules of probability calculus; and that if A is preferred to B and B to C, then there exists a gamble involving A and C which is judged indifferent to B. Their discussion is limited to linear utility. They conclude with some suggestions on deriving the utility function for an individual through experimentation.

Fishburn [Ref. 10] is critical of the linear utility approach because experimental evidence indicates that people's reasoned judgments often violate the basic axioms of expected utility. He categorizes the criticisms of linear utility theory as descriptive and normative. He defines these categories as:

> The descriptive approach seeks to identify patterns in an individual's preferences or actual choices and, subsequently, to develop a model that characterizes these patterns and which can be used to predict preferences or choices not yet revealed.... Descriptive theory is interested in actual choice behavior rather than in guidelines or criteria for "right" decisions.... The normative approach is concerned with criteria of coherence, consistency, and rationality in preference patterns that, as in linear utility theory, are often set forth as axioms.... Applications of normative theory should entail careful reasoning and evaluations so that it is imperative for a "right" decision to be carried out properly [Ref. 10: p. 26].

His primary criticism is in the common violation of the axioms of linear utility theory. Primarily the independence axiom and the commonly observed preference reversal phenomenon. His major point here is for a normative model, certain axioms must hold. These are the reduction principle, asymmetry of strict preference, and first degree stochastic dominance. He proposes the use of nonlinear utility tailored to the specific type problem encountered and the desired utility measure. His proposals cover everything from minor relaxations of linear utility theory which still preserve linear utility to nonlinear utility measures which account for independence violations.

Utility theory is a critical pillar of decision theory. As such, it underlies the majority of the solution methodologies in all areas of research. While the theory is not perfect in describing human behavior and it is difficult to obtain accurate utility mappings from people, there is still a great deal of worth in developing utility functions for use in our model.

B. GAME THEORY

Luce & Raiffa [Ref. 8] develop the use of games in decision making from the basic two-person zero sum game through two-person non-zero sum games to n-person games. The development of n-person game theory is an important consideration for our model, due to the large number of agencies involved in decision making. The normal form of the n-person game consists of:

- The set, I_n, of n players.
- The n strategy sets $S_1, S_2, \ldots, S_n$.
- The n real-valued payoff functions $M_1, M_2, \ldots, M_n$, where $M_i(s_1, s_2, \ldots, s_n)$ is the utility payoff to player i when player 1 uses strategy s_1, 2 uses s_2, ..., and player n uses s_n.

It is assumed that each player knows the entire structure of the game in normal form and each is driven by an inflexible desire to maximize expected utility. They develop the idea of behavioral strategies where the player defines a probability distribution over the alternatives of each information set. The problem of collusion among players and methods to address this behavior are developed. Issues concerning bribes and pre-play communication are discussed and limitations in the theory become more evident. From this discussion the most promising approaches for our application appear to be:

- Games with solutions
- Games with ψ-stability

Games with solutions are games that allow bribes , have full pre-play communication, allow correlation of strategies in coalitions, and have transferable utility. Games with ψ-stability are games that allow bribes, have partial pre-play communication, allow correlation of strategies in coalitions, and have transferable utility.

The games with solutions require that a concept of imputation[1] dominance be developed whereby a definition of a solution is given as a set, A, of imputations such that:

- If x and y are in A, neither x nor y dominates the other.
- For any imputation z not in A, there is at least one x in A such that x dominates z.

The major argument against the solution method is the question of multiple solutions and how to choose the one that is played. Their proposition is to reiterate von Neumann and Morgenstern's position that this is outside the framework of the game. Games with ψ-stability are games with a solution that differs from the solution discussed previously. In this case a solution is defined as an imputation *and* a coalition structure. One characteristic of these type games is that the equilibrium arises from strategic possibilities *as well as* from communications limitations. There are three major shortfalls in this type game:

- The ψ function is not generally explicit in social situations and no theory exists for determining it.
- The ψ-stable pairs are not generally unique and we have no method by which to choose one solution.
- Players are assumed to have far too limited future vision which induces improbable behaviors.

The discussion of group decision making is developed by Luce & Raiffa [Ref. 8] by demonstrating the many problems with `mapping many individual preference functions into one societal function. Several methods were demonstrated to overcome these problems including Nash's development of bargaining in a social context, establishment of a common unit and base of reference, and using roles of individuals to develop potential orderings of values for the group. Bartos [Ref. 9] develops the Nash idea fully and offers a rich explanation of the major divergence of Nash and traditional game theory. Nash proved that an equilibrium solution exists for games where each player is maximizing their

[1] Imputation- solutions to the game that are consistent with rationality rules and which preserve Pareto optimality.

payoff given the behavior of the other players. However, multiple equilibria cause the Nash solutions to fail just as the n-person game models fail. Eichberger [Ref. 11] proposes using the Nash equilibrium model and solution method, then using learning to guide the player's decision making when he plays the game the next time. This method holds promise if the learning behavior can be accurately captured and modeled in a complex system.

Game theory holds some promise for developing the decision making logic for our model. However, one major problem underlying game theory is the requirement to enumerate all possible outcomes and strategy sets available to each player as well as identify the appropriate utility functions and probability vectors over the outcomes.

C. PROBABILISTIC MODELING

Pearl [Ref. 8] develops the use of Baysian inferences to drive decision making by developing a Baysian network[2] and applying facts until an effect is observed. The effect is a probability distribution across a set of potential outcomes. For a complete discussion of Baysian updating, consult a Baysian statistics or probability theory book. If we imagine the network to be a still pond and new information a pebble, the propagation of the knowledge in the network is like dropping the pebble into the lake. Pearl develops a conceptually strong model for propagating beliefs in a causal network. He explicitly develops methods for coping with typical network problems such as looping and demonstrates techniques for propagating beliefs through a variety of network structures and combinations. Neapolitan [Ref. 12] develops a similar model but does so more from a mathematic point of view. He includes a very complete set of algorithms for implementing this model. He goes to great lengths to rigorously develop the theory and explain the rational for using this technique in conjunction with an expert system.

This methodology offers a means for determining probable outcomes from information that is uncertain. By combining this idea with either a knowledge based

[2] Baysian network- a directed graph of dependency representations among a collection of variables.

system or a game theoretic approach, we can place probability distributions over the outcomes of a game or develop beliefs (perceptions) of the state of the world.

D. KNOWLEDGE BASED SYSTEMS

Knowledge based systems are designed to capture the intricacies of human cognitive abilities and apply them to a large variety of problems. The general form of a knowledge based system is for the system to have a database of information, knowledge, and a set of logical operators to probe the database and reach conclusions. Based on the conclusion reached, actions can be taken or further analysis can be done. As in the probabilistic approach, new data added to the database has the effect of propagating throughout the system.

One specific area which has potential for our application is the use of multiple intelligent agents to determine the solution to the problem. This field of artificial intelligence is known as distributed artificial intelligence because the agents are usually distributed over several processors[3] or the problem is subdivided and distributed over several small problem solvers. Werkman [Ref. 13] develops a model for negotiating the solution to a problem when the agents are attempting to cooperate. To resolve conflicts due to perceptions, the agents share perception information which helps each agent reevaluate his priorities based on the new knowledge. The negotiation is facilitated by a negotiator agent who intervenes whenever the other agents become deadlocked. The benefit of this approach is that it allows for an audit trail of cause and effect for each decision made by the group. In addition, there is no need to enumerate all the possible courses of action available to the system as it can potentially develop its own courses of action from a limited set of primitives.

This approach would be beneficial for modeling the military staffs or the theater level agents who are attempting to cooperate to solve the problem (e.g. UN mission or US Country Team). Coupled with this idea would be to use the Baysian updating concept discussed above to build probability distributions to reflect the uncertainty of the situation.

[3] This allows parallel processing to occur.

This is very attractive due to the Baysian updating which is already incorporated into the model. The concept of utility will need to be used no matter which approach is used. Through the utility function we can valuate the potential solutions for each player. At the very least this will help to identify areas of conflict that must be resolved. Modeling the cooperative agents (coalitions) with distributed artificial intelligence techniques and negotiation coupled with the Baysian belief propagation could help circumvent the problems inherent with n-person game theory. Finally, to capture the decision making process of the opposing forces we could consider the use of two-person games where each player in that game is a group of people who have already negotiated their courses of action and the game is solved repeatedly for Nash equilibria.

V. MODEL

A. MODEL OVERVIEW

The proposed decision making model is largely based on the concepts of decision theory, including multi-attribute utility, and structuring the problem as a decision tree. The overall model structure is as follows:

- The DM determines the relative weights of the attributes used in his multi-attribute utility function.
- The weights are checked for consistency and are used to build a composite utility function.
- The sensor model observes each node in the theater to build a threat and a civilian aid requirements forecast for each node.
- Based on the forecasts and applications of Bayes rule, decision probabilities are calculated and applied to the appropriate decision tree.
- Based on the forecasts, expected outcomes are calculated on each branch of the decision tree.
- Utility values for each outcome are calculated.
- A rollback algorithm solves the decision tree using a maximum expected utility criteria for the optimal course of action (COA) at that node.
- The process is repeated for each node in the theater resulting in a list of potential COAs for each node and the expected utility attained by executing that COA.
- The final course of action is determined by applying the resource constraints to the list of node COAs.
- The plan is executed in the model and actual results are calculated.
- The forecast model and world state are updated.
- The process reiterates for the next planning cycle.

The decision model is designed to replicate the decision making process at the theater staff level. The same decision structure is appropriate for any single side in the theater as long as the appropriate modifications are made to the attribute ranks and the forecasts.

1. Assumptions

The model makes a variety of assumptions in several key areas. The majority of these concern the development of the utility model which constrains the final form of the multi-attribute utility function to an easily manageable form. To aid in the understanding of the assumptions, they are categorized by the application domain and their effect on the model is explained.

- The appropriate form of the utility function in each attribute for the DM is in the form of a logarithmic non-linear function. This implies the DM exhibits an increase in risk aversion as the payoffs increase in each attribute relative to the DM's reference scale.
- The DM's preferences across the utility attributes follows the Von Neumann and Morgenstern axioms for preference. This implies the DM should choose among alternative COAs using an expected utility criterion.
- The DM's preference rankings among the attributes exhibits mutual preferential independence. This implies the DM's ranking of the attributes remain unchanged when considered in combination.
- The Lanchester model of attrition using the square law is appropriate when considering any non-ambush type combat action by one side against another. This implies that the sides will use aimed fires during direct fire combat and they want to minimize collateral damage to civilians.
- The Lanchester model of attrition using the mixed law is appropriate when considering any ambush type combat action by one side against another when no civilians are present. This implies the side caught in the ambush will apply unaimed fire during the ambush.
- The DM's relative ranking of his desire to minimize collateral damage to civilians can be used to modify, decrease, the attrition rates for that side from their maximum value when civilians are present. This implies that each DM enforces more stringent rules of engagement when civilians are present, relative to his desire to prevent civilian casualties.
- The attrition rate for civilians due to starvation can be calculated as a function of their current supply and health status. This function is a linearly decreasing function in days of supply. This implies the civilian attrition due to starvation and disease is variable based on their current state of supply.
- The Bonder-Farrell approach to estimating the attrition coefficients for each side is sufficient for determining an appropriate attrition coefficient. This implies that the only data required to compute the attrition rates for each side are the aggregated probability of a single shot kill and the approximate exposure time required to acquire and shoot at a target.
- Any COA combination planned can be completed during the planning cycle for the model. This implies that all executed COAs begin at the same time after the planning cycle is complete and no new missions are started until all previous missions are completed.
- Assumptions for data elements include:

Probability of a single shot kill for U.S.= 0.7 and OPFOR= 0.6.

Exposure Time to fire one shot = 5 seconds.

Exposure Time to acquire target (minimum) 10 seconds.

Exposure Time to acquire target (maximum) 60 seconds.

Lethal Area of a Round = 2.0 square meters.

Target Area = 10,000 square meters.

Civilian Consumption Rate = 2 pounds per person per day.

Civilian Starvation Rate = 0.005

Minimum Aid Delivery = 7 Days of Supply

2. Limitations

The model is limited in scope and problem domain. These limitations are mainly concerned with the problem domain and the level of detail present. The limitations are listed with no explanation concerning their impact on model performance except where the limitation is seen as potentially problematic.

- The model is applicable to OOTW contingency operations in general and humanitarian assistance missions in particular.
- The model considers only five attributes in the formation of the multi-attribute utility model. These attributes were chosen to capture the essence of the conflicting demands in the humanitarian assistance mission area.

B. FORECASTS

One of the major conceptual underpinnings of the model concerns the use of forecasts to predict the threat and civilian aid requirements for each node. The forecasts are used so that the model does not make decisions under certainty. The decision logic is insulated from the ground truth model state by the forecasts. The forecasts are discrete probabilities that a particular state of the world will be attained once a course of action is implemented. The concept of the forecast is examined using the threat forecast as an example and the structure of the civilian aid requirements forecast is presented without an in-depth discussion of the development.

1. Threat Forecast

The threat forecast is a probability forecast to predict the level of threat anticipated at a particular node coupled with a perturbed estimate of the enemy strength at that node. The level of threat is determined using a three point scale (states):

- Hostile
- Possibly Hostile
- Not Hostile.

The forecast is initialized with each state; $i = 1, 2, 3$; being entirely predictive of the end state. The number of samples used to seed the forecast is predetermined by the user. Four samples for the model runs are used for the analysis of the model. This parameter is important because as the number of samples increases the rate of change in the forecast decreases. Thus, there is an expectation that there is some finite upper bound on the size of this parameter. The forecast then collects data on the actual state of the node, if determined during a planning cycle, and updates the probabilities as appropriate. A sample of the forecast can be found in Table 5.1. In the table, TA represents the actual threat state and TF represents the forecasted threat state.

State i	Marginal Distribution $p_{TF}(i)$	Hostile (TA=1)	Not Hostile (TA=0)	Total Samples	Decision Probabilities p(TA=1|TF)
1. Hostile	0.25	1	0	1	1
2. Possibly Hostile	0.5	1	1	2	0.5
3. Not Hostile	0.25	0	1	1	0
Total Samples		2	2	4	

Table 5.1. Initialized Threat Forecast, N=4

The probabilities in columns two and six are the marginal probability of the forecast state i being attained, and the probability of the threat being hostile given a forecasted state. These probabilities are used in the decision tree to formulate the expected utility on any branch of the tree. As the forecast is updated, the probabilities change in accordance with Bayes rule and the laws of probability. For example, if the DM chose to actually send a unit to a node, the actual state of the threat at that node would become known at that time. That is, the threat would either engage the unit or not. If the DM sent the unit to that node and the threat was in fact hostile, the probabilities would be updated as shown in Table 5.2.

State i	Marginal Distribution $p_{TF}(i)$	Hostile (TA=1)	Not Hostile (TA=0)	Total Samples	Decision Probabilities p(TA=1|TF)
1. Hostile	0.2857	2	0	2	1
2. Possibly Hostile	0.4286	2	1	3	0.6667
3. Not Hostile	0.2857	1	1	2	0.5
Total Samples		5	2	7	

Table 5.2. Updated Threat Forecast, N=7

The updates are calculated by applying the rules of total probability and Bayes' Rule. Let the joint probability mass function of the threat forecast, TF, and the actual threat, TA, be denoted by

$$p_{TF,TA}(i,j) = \Pr\{TF = i, TA = j\},\ i \in TF,\ j \in TA \tag{5.1}$$

and the probability mass function for TF, p_{TF} , has as its i-th element

$$p_{TF}(i) = \Pr\{TF = i\},\ i \in TF. \tag{5.2}$$

This vector gives the relative frequency of each forecast and is found by summing the joint probability mass function in Equation (5.1) across all values of j. The actual outcome, TA, has a probability mass function, p_{TA}, where the j-th element is

$$p_{TA}(j) = \Pr\{TA = j\},\ j \in TA. \tag{5.3}$$

This vector gives the relative frequency of each outcome and is found by summing the joint probability mass function in Equation (5.1) across all values of i. Using the multiplicative law of probability, the elements of the conditional probability matrix **P** of a particular outcome, $j \in TA$, given a particular forecast, $i \in TF$, $p_{TA|TF}(j|i)$ and the elements of the conditional probability matrix **F** of a particular forecast, $i \in TF$, given a particular outcome, $j \in TA$, $p_{TF|TA}(i|j)$ are obtained. These are given as

$$p_{TA|TF}(j|i) = \frac{p_{TF,TA}(i,j)}{p_{TF,TA}(i,1) + p_{TF,TA}(i,0)}, \; i \in TF \text{ and } j \in TA \tag{5.4}$$

and

$$p_{TF|TA}(i|j) = \frac{p_{TF,TA}(i,j)}{\sum_{k \in TF} p_{TF,TA}(k,j)}, \; i \in TF \text{ and } j \in TA. \tag{5.5}$$

The **P** matrix is known as the decision probability because these are the probabilities that will be used in the decision tree by the DM. The **F** matrix is the likelihood of the forecast given a certain outcome. Applying Bayes' rule results in the following relationships:

$$p_{TF|TA}(i|j) = \frac{p_{TA|TF}(j|i)p_{TF}(i)}{p_{TA}(j)}, \; i \in TF \text{ and } j \in TA, \tag{5.6}$$

and

$$p_{TA|TF}(j|i) = \frac{p_{TF|TA}(i|j)p_{TA}(j)}{p_{TF}(i)}, \; i \in TF \text{ and } j \in TA. \tag{5.7}$$

The joint probability, that a particular forecast will be made and a particular outcome of hostile or not hostile will occur, can be estimated by dividing the entries in the body of Table 5.2 by the total number of samples, seven. From the row sums the marginal probability mass function of TF is determined to be

$$\mathbf{p}_{TF} = (0.2857, 0.4268, 0.2857). \tag{5.8}$$

Similarly from the column sums, the marginal probability mass function for TA is

$$\mathbf{p}_{TA} = (0.71, 0.29) \tag{5.9}$$

These are the fraction of the time the threat was hostile or not at this node. The decision probabilities $p_{TA|TF}(j|i)$ are found using Equation (5.4) and are partially shown in Table 5.2.

The threat forecast is sensitive to the value chosen for the initial sample size. If, in the example the forecast were seeded with 20 samples the outcome after the update would be as shown in Table 5.3. The result is a change of 0.0248 (0.2857 to 0.2609) in the measure of the marginal probability of forecast state three and, more importantly, of 0.3333 (0.5 to 0.1667) in the conditional probability of TA, given the particular state probability forecast TF. From this example it is easy to see how the change in sample size could potentially alter the outcome of the decision making policy over the course of many planning cycles. As a result, a sensitivity analysis must be done to determine an upper and lower bound for the sample size to use in seeding the forecast.

State i	Marginal Distribution $p_{TF}(i)$	Hostile (TA=1)	Not Hostile (TA=0)	Total Samples	Decision Probabilities p(TA=1|TF)
1. Hostile	0.2609	6	0	6	1
2. Possibly Hostile	0.4783	6	5	11	0.5455
3. Not Hostile	0.2609	1	5	6	0.1667
Total Samples		13	10	23	

Table 5.3. Updated Threat Forecast, N=23

The final portion of the threat forecast is the measure of threat strength at the node. This forecast strength value is used in the calculation of the expected payoff for each possible course of action under consideration. The value is calculated by fitting a normal distribution with a mean of the ground truth threat strength and a variance of 0.3 times the enemy ground truth strength. This distribution is then randomly sampled, which results in an estimate of the threat strength at the node with induced error. The error induced is directly controllable by the value selected to represent the variance of the normal distribution. This variance can be manipulated by the user to represent a variety of intelligence gathering capabilities or assets. Care must be taken to insure that the fitted distribution does not report a negative strength value. To prevent this, a safeguard has been included that has the model draw another sample in the event the user has specified a large variance, which results in a negative threat strength at the node.

This results in a probability forecast at each node in the theater, and a threat strength forecast. The probability forecast is updated as the DM implements COAs, and the strength forecast is updated every decision cycle. Some of the probability forecasts may never be updated if the DM never physically enters the node concerned. The strength forecast should remain highly correlated to the actual threat strength on the node, even as the threat strength numbers fluctuate through combat and reinforcement.

2. Civilian Aid Requirements Forecast

The civilian aid requirements forecast is fundamentally the same as the threat forecast. It has different states and added criteria for how the forecast is updated during the decision cycle and after delivery of aid. A sample civilian aid requirements forecast is shown in Table 5.4. The determination of the criticality of the need is based on the number of days of supply the civilians have at the time of the forecast. If the civilians have one or fewer days of supply, they are considered critical.

State I	Marginal Distribution $P_{CF}(I)$	Critical (CA=1)	Not Critical (CA=0)	Total Samples	Decision Probabilities p(CA=1|CF)
1. Critical	0.3462	2	7	9	0.2222
2. Possibly Critical	0.3462	2	7	9	0.2222
3. Not Critical	0.3077	1	7	8	0.125
Total Samples		5	21	26	

Table 5.4. Sample Civilian Aid Required Forecast, N=26

The civilian status will be known with some certainty after a DM sends a unit to a node. If the unit delivers some aid, the status of that node will likely become less critical than before the unit arrived. As a result, the forecast will necessarily need to be adjusted in the next evolution by incorporating the knowledge that the unit has delivered a number of days of supply to the node. To achieve this, the forecast is reset to the initial state and n, the number of days of supply delivered, samples are added to each cell in the not critical column. As a result, the forecast is adjusted to represent the number of days supply the U.S. forces believe they left in place.

The updating of the forecast during the normal decision cycle differs from that of the threat forecast. Because the criticality of need is dependent on the amount of time between aid deliveries, these forecasts will be updated on every decision cycle in two ways. The first case, if aid has not been delivered previously, will be accomplished by adding one sample to each cell of the critical column of the table on each decision cycle. The second case, if aid has been delivered previously, will be accomplished by decrementing the critical column by one on each decision cycle until the forecast is at its original state. After this state is reached, the critical column is incremented by one on each decision cycle. This technique will insure the sensitivity of the forecast to changes in the perceived aid requirements at a node. Thus, the consumption of aid by the civilian populace is captured in the forecast as a function of time (decision cycles).

The civilian strength is forecast in the same manner as the threat strength value, however, the updating of the threat forecast is done in a different manner. The threat forecast is updated during any decision cycle a friendly unit arrives at a node. The update is accomplished by adding one to the hostile column if the unit is attacked or one to the not hostile column if not attacked. This estimate is used in the projection of the utility for assisting these people. Again, the same caveats apply as to arriving at a projected strength less than zero, and on determining the parameter value for the variance.

Once the forecasts are calculated, the results are applied in determining the optimal decision and the expected utility gained from following a specific COA at that node. The forecast probabilities are used in the determination of the level of uncertainty inherent in following a specific COA. The strength forecasts are used to determine the expected utility gained from following that COA and encountering the projected strengths. This leads to a discussion of the decision structure required to build the decision trees used to solve the problem.

C. DECISION STRUCTURE

The decision to follow a specific COA can be thought of as a series of events and information in time that lead to a specific outcome. A commonly accepted manner of representing this type of problem is through the use of influence diagrams and decision trees. The influence diagram depicts a sequential development of information and events that converge to realize an outcome. In these diagrams, random events, like forecasts, are depicted using a circle. Decision opportunities are represented as squares and outcomes are diamonds. The decisions of interest here are limited to combat, aid, or ignore. The flow of information and influence (dependency) is depicted by directed arcs. If the problem is one of what COA should be taken with respect to a certain geographic area, or node, it can easily be formulated as an influence diagram to capture the elements of concern. Figure 5.1 depicts this relationship.

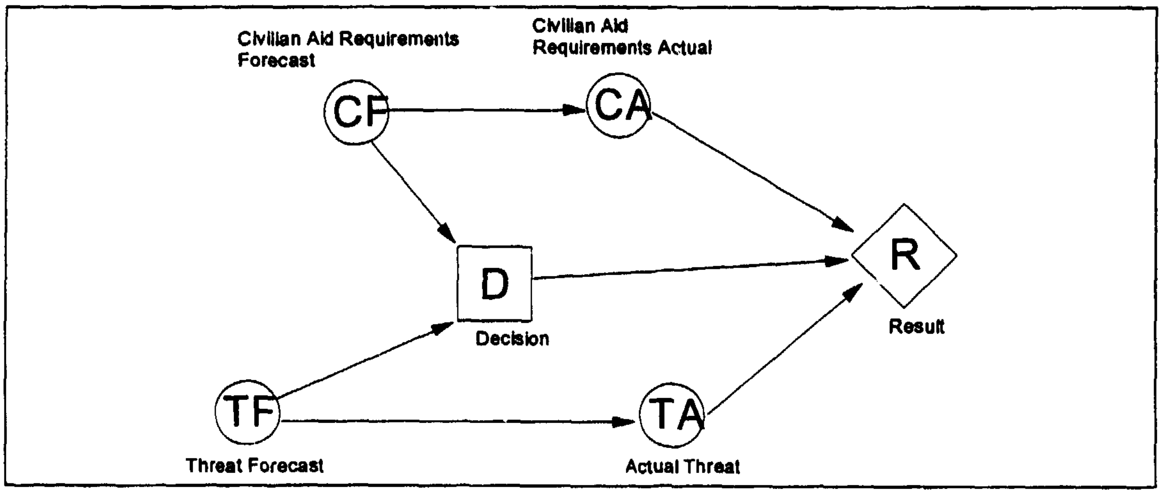

Figure 5.1. Influence Diagram.

The flow of information and dependency is crucial to developing the appropriate logic to solve the problem. In this formulation, the threat forecast is determined before the civilian aid requirements forecast. Together they influence the decision as to the appropriate COA to follow. The forecasts, in turn, influence actual realizations of the threat and civilian aid requirements. In reality, the actual realizations condition the forecasted values, but they are not known before the decision is known, and hence the directed arcs from the forecasts to the realizations. The combination of the realized world state, civilian aid requirements and threat, and the COA decision produces an outcome which is translated into a utility result. These relationships can now be enumerated to consider all possible combinations of forecast state, decision, and expected outcome. From these combinations, the DM will pick that combination which results in his maximum gain in utility.

The construction of the decision tree to solve this problem then becomes relatively simple. Starting at the leftmost edge of the influence diagram, the states at each node are enumerated until reaching the rightmost edge of the influence diagram. The problem now becomes one of applying the probabilities calculated from the forecasts to the appropriate arc of the decision tree. Once this is done, and the expected outcomes are calculated from the utility function, the expected utilities from the rightmost edge of the decision tree, the result nodes, to the leftmost edge, the threat forecast, are found. At each confluence of branches the DM chooses the maximum utility from the converging branches to continue calculations in subsequent branches. This method of calculating the expected utility is known as the rollback, or foldback, algorithm. This algorithm guarantees the solution of the path or paths that has the highest associated utility. The resulting path is the decision policy for that node at that time.

In an attempt to reduce the complexity of this potentially lengthy calculation, this study uses forecasted strengths to eliminate certain branches. If there is a prediction of no civilians at a node, there is little use in calculating any result contingent on civilians being present. The same logic holds when considering the threat strength forecast. As a result, the influence diagram and induced decision trees are reduced in these instances, as shown in Figures 5.2 and 5.3.

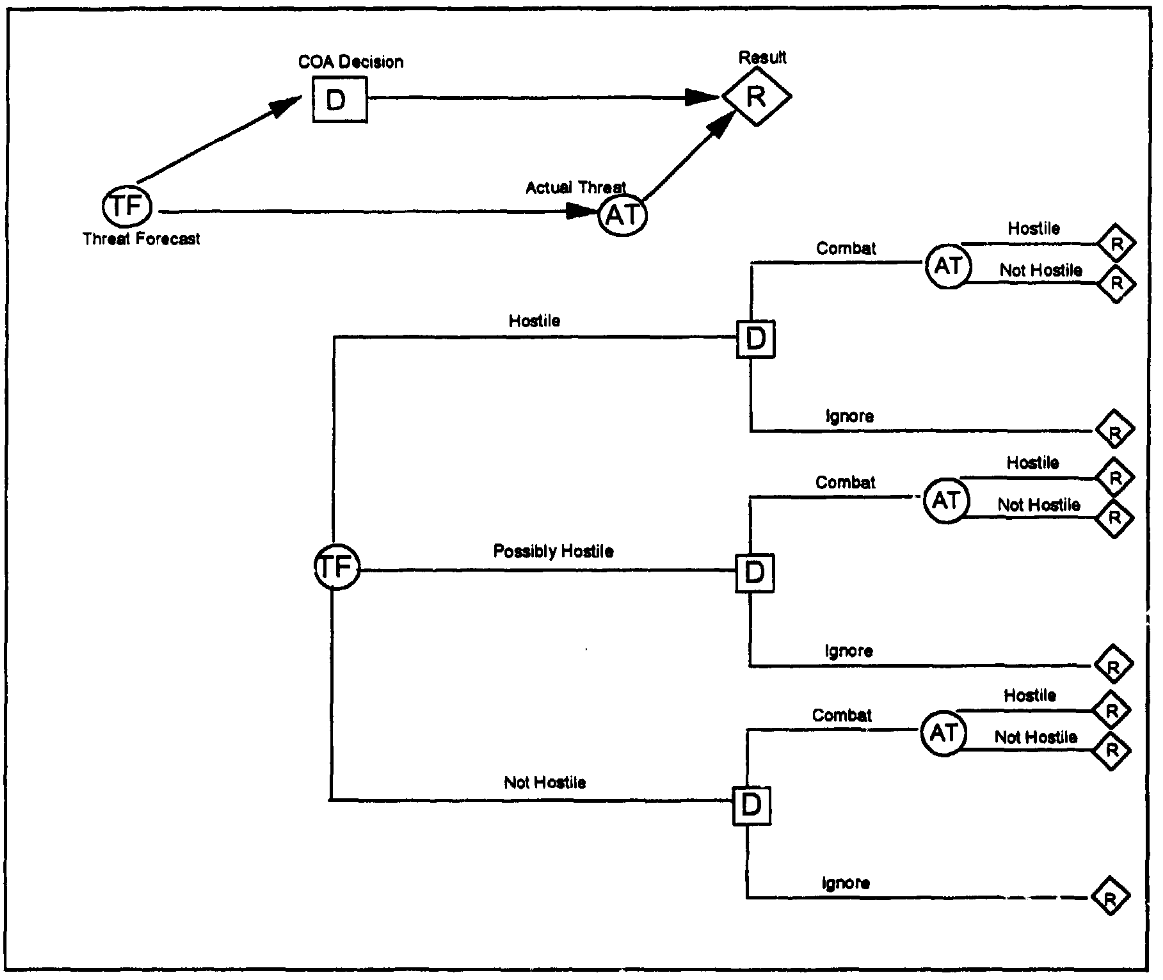

Figure 5.2. Threat Only Influence Diagram And Decision Tree

The result of these calculations is an optimal decision, in terms of utility, for each node in the theater. The COA is formed by noting the mission to be performed (combat, aid, or ignore) and the required resources to successfully accomplish the mission. In the case of a combat action (combat) the required resource is combat forces. As a result, appropriate Lanchester equations are used to determine the expected force required to win the engagement. This value becomes the minimal resource, in terms of soldiers, required to succeed in engaging the expected threat strength and winning. In the case of the aid mission, the resources are aid and combat soldiers for security. The aid required is calculated based on the estimated civilian strength value and an assumed consumption rate. The goal for success is to provide three days of supply to the civilians and to provide

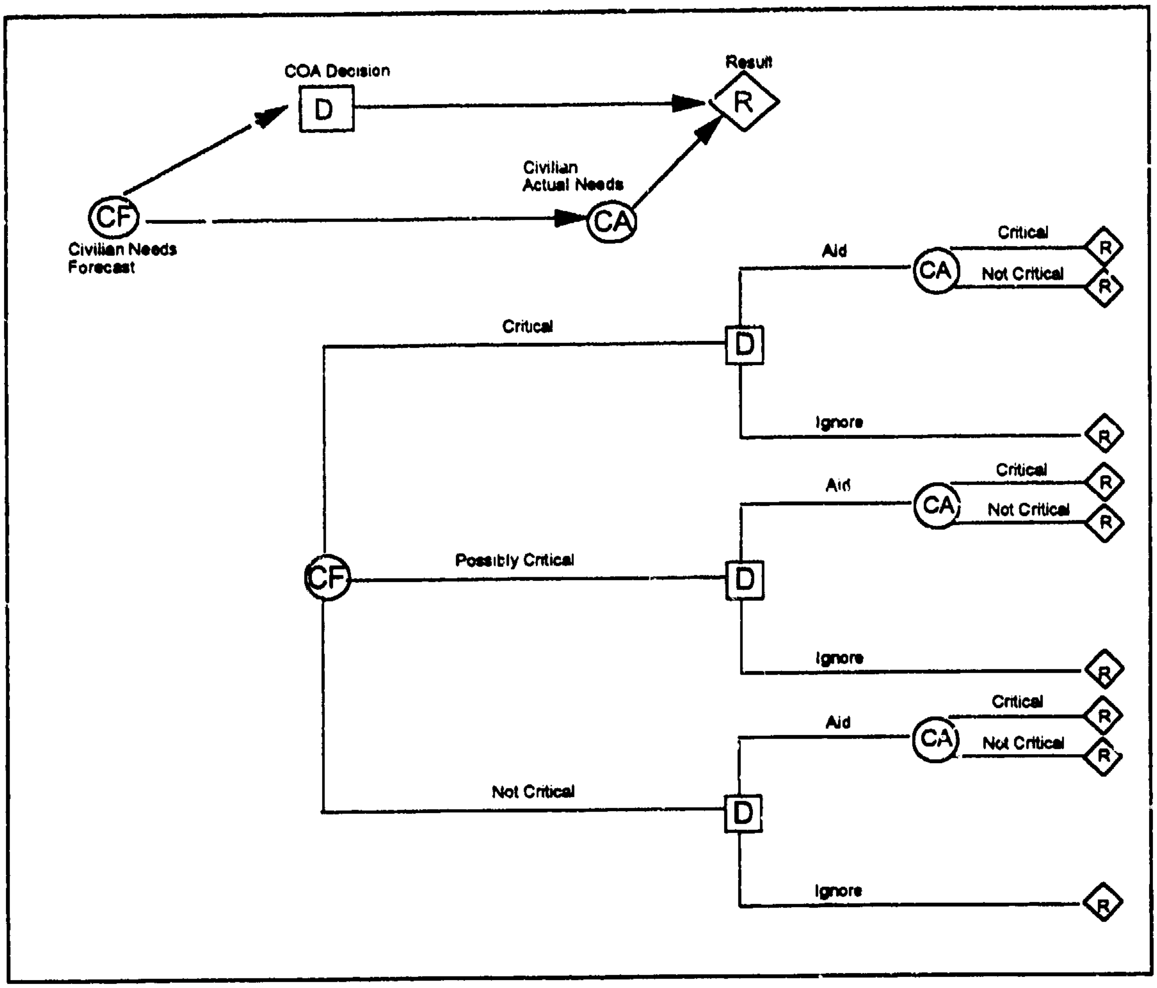

Figure 5.3. Civilians Only Influence Diagram And Decision Tree

enough combat power to defeat an ambush. These COAs have an associated utility value based on the outcome of the mission. This leads to the development of the utility functions for the model.

D. UTILITY DEVELOPMENT

The development of the utility function for the DM is based on the utility theory developed by Von Neuman and Morgenstern. The development of the utility functions is based on the relative importance the DM places on the attributes of interest. In this case, the following five attributes are considered:

- Friendly Casualties (FC)- The desire to reduce the exposure of friendly forces to combat action.
- Enemy Casualties (EC)- The desire to impose as much destruction on the enemy forces as possible.
- Civilian Casualties Due to Combat (CC)- The desire to reduce collateral damage to civilians in any combat action.
- Civilian Casualties from Lack of Aid (CA)- The desire to provide the humanitarian assistance and reduce the suffering of the civilian populace.
- Aid Delivered (AD)- The desire to provide aid to the civilian populace. This attribute uses days of supply delivered as its basic unit of measure.

Some readers may question the inclusion of two attributes, CA and AD, which seemingly measure the same quantity, civilian suffering. The rationale for including AD was to attempt to quantify the more difficult aspects of the OOTW humanitarian mission. In this case, the delivery of aid was used as a surrogate for any other quantity of interest. One could just as easily substitute control of geographic regions. This attribute is intended to capture the idea of imparting some semblance of order to the country in question. Future versions of this model could change this variable, to select an attribute to more closely model the theater in question. The remaining attributes seem to be present in any OOTW humanitarian assistance mission in a hostile environment.

The model described by Marshall and Oliver [Ref. 14] is used to build the multi-attribute utility function for the DM. It begins by assigning a separate non-linear utility function to each attribute. Let R_j be the set of possible results for attribute j where j= 1, 2, ..., n. It assumes that a preference ordering is defined on each of these sets. Let u_j be a utility function defined on R_j and let w_j be a relative weight assigned to attribute j. Let r_j be an element of R_j and $\mathbf{r} = (r_1, r_2, ..., r_n)$. The scalar utility resulting from this vector of attributes is

$$U(\mathbf{r}) = \sum_{j=1}^{n} w_j u_j(r_j). \tag{5.10}$$

In order for this decomposition of $U(\mathbf{r})$ to hold, it must be assumed that there is a transitive preference ordering defined on each set R_j , and that the attributes exhibit mutually preferential independence. In addition, the weights w_j must sum to one.

To determine the utility function form, the DM's relative importance of attributes must be captured. To this end, pairwise comparisons of each attribute will be used to derive the relative weights of the attributes. Consider the weights of the attributes, w_j, and the relative rankings of a pair of attributes, a_{ij}. If a nine point scale as shown in Table 5.5 is used, the relative weights associated with the attributes can be calculated. The use of the nine point scale is based on the original work in the Analytic Hierarchy Process as developed by Saaty [Ref. 15] and further improved by McQuail [Ref. 16].

Scale Value	Interpretation
1	The attributes are of equal importance.
3	Attribute is slightly more important.
5	Experience or professional judgment show the attribute is more important.
7	Attribute is demonstrably more important.
9	Attribute is absolutely more important.
Note: Intermediate values 2,4,6,8 are used to show intermediate values.	

Table 5.5. Nine Point Scale For Rankings

The Least Squares Fit (LSF) technique, as developed by Morin [Ref. 17], is used to solve for the weight vector, **w**, for a given matrix **A** = $[a_{ij}]$. The matrix **A** is a square matrix (n x n) containing the pairwise comparisons of the attributes based on the nine point scale. For any comparison a_{ii}= 1 and for **A** to be completely consistent, the a_{ij} entries must meet the following criteria:

$$a_{ij} = \frac{1}{a_{ji}}. \tag{5.11}$$

A LSF expression that solves for the error between the weights and pairwise ratios is

$$e(w) = \sum_{i=1}^{n}\sum_{j=1}^{n}\left(a_{ij} - \frac{w_i}{w_j}\right)^2. \tag{5.12}$$

Using the relationship $a_{ij}w_j = w_i$, a more tractable, equivalent measure of error is

$$e(w) = \sum_{i=1}^{n} \sum_{j=1}^{n} (w_i - a_{ij} w_j)^2. \tag{5.13}$$

The vector w that best fits an over-determined matrix (consistent or not) is the vector of weights w that minimizes the error in the above equation subject to the constraint

$$\sum_{i=1}^{n} k_i w_i = 1. \tag{5.14}$$

In the above constraint, the value of k_i depends on whether the comparison matrix is being used to derive probabilities or priorities. The attempt here is to obtain the preference indifference probabilities of the DM between the riskless alternative and the risky venture. Hence, the sum of the w_i over all i is one, and as a result, the $k_i = 1$ for all i. Using the method of Lagrange Multipliers to solve for the best fit vector **w**, the indifference probabilities for the DM are obtained. Hypothetical weights were determined for this model.

Once the indifference probabilities are obtained, the construction of the utility function for each attribute is accomplished by assigning a non-linear function to each attribute over the range of outcomes. A logarithmic form of non-linear utility is used to model the relative utility gained for each outcome in the sample space. The logarithmic form of the utility function is used based on the argument posited by Marshall [Ref. 14] that the logarithmic form exhibits a more appropriate risk aversion behavior as a function of the payoff size. In essence, for payoffs that are small relative to ones total worth (in an attribute), a DM is more likely to exhibit less risk aversion than if the payoff were large relative to ones total worth. The logarithmic form of the utility function exhibits this type behavior. For a complete explanation the reader is referred to the reference cited.

The form of the utility function used is taken from Marshall [Ref. 14] and is given by

$$u(r) = a \log\left(1 + b\left(\frac{r-\underline{r}}{\bar{r}-\underline{r}}\right)\right), \underline{r} \le r \le \bar{r}. \tag{5.15}$$

In this formulation, $\bar{r}$ is the best result and $\underline{r}$ is the worst result obtained in a given attribute. For example, if there were 10,000 friendly soldiers in the theater, the best result in terms of friendly casualties (FC) would be 0 and the worst result would be 10,000. By setting r equal to the worst value it can seen that u(r)=0 for any values of a and b. Conversely, by setting r equal to the best result, it can be shown that the following relationship must hold:

$$a = \frac{1}{\log(1+b)}. \tag{5.16}$$

In this case, the parameter a is completely determined by the parameter b. To determine a suitable value for b, it is necessary to look at the ratio of marginal returns from an extra unit of r near the worst value for r and near the best value for r. This ratio measures the relative slopes of the utility function at $\bar{r}$ and $\underline{r}$. β is defined to be the ratio of the slope of the utility function at the worst level to the slope at the best level.[4] This leads to β = b+1 and the utility function becomes

$$u(r) = \frac{\log\left(1+(\beta-1)\left(\frac{\bar{r}-r}{\bar{r}-\underline{r}}\right)\right)}{\log\beta}, \underline{r} \le r \le \underline{r}. \tag{5.17}$$

In this study, the utility functions are built for each attribute by determining the values for β, $\bar{r}$, and $\underline{r}$ for a hypothetical DM. For applications of this model to real problems, the values for β would be determined by questioning the appropriate DM. Once these values are determined, the component utility functions for each attribute can be formed, as shown in Table 5.6.

The composite utility function, U(r), is formed by combining the weights obtained with the utility functions for the component attributes and summing the resulting utilities for any given outcome. In order to evaluate the utility functions for a specific instance (outcome), the expected number of casualties or aid delivered must be determined. To this end, an appropriate attrition model to obtain the expected numbers of casualties in any given instance must be derived.

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[4] Another way to view the parameter β is as a measure of risk aversion as β gets larger the DM is more willing to accept risk.

Attribute	β	Best Value (1000's)	Worst Value (1000's)	Utility Function
Friendly Casualties (FC)	2	0	10	$\ln\left[1+\frac{r}{-10}\right]/\ln 2$
Enemy Casualties (EC)	10	20	0	$\ln\left[1+9*\frac{r-20}{20}\right]/\ln 10$
Civilian Casualties Due to Lack of Aid (CA)	5	0	500	$\ln\left[1+4*\frac{r}{-500}\right]/\ln 5$
Civilian Casualties Due to Combat (CC)	5	0	500	$\ln\left[1+4*\frac{r}{-500}\right]/\ln 5$
Aid Delivered (AD)	6	30	0	$\ln\left[1+5*\frac{r-30}{30}\right]/\ln 6$

Table 5.6. Utility Function Forms[5]

E. ATTRITION MODEL

The development of the attrition model used in this model is based on the work done by Lanchester as discussed by Lindsay [Ref. 18]. The environment in which OOTW operations are conducted is significantly different from the environment under which the original Lanchester equations were derived. As a result, various combinations of Lanchester equations are used to fit certain hypothetical engagement types. For these purposes, consideration is given to combat actions against enemy forces with civilians present, combat actions against enemy forces without civilians present, aid deliveries with civilians present, and aid deliveries without civilians present.

The development of the attrition model is based on the premise that when civilians are present, the friendly forces will be constrained in their application of force by some rules of engagement (ROE). To capture the effect of these ROE on the friendly forces' ability to bring their firepower to bear on the enemy, the attrition coefficient for the friendly forces attriting enemy forces is modified as a function of the importance placed on civilian casualties by the DM, and the maximum attrition coefficient attainable if civilians

5 The graphs of these utility functions can be found in Appendix C.

were not present. A linear function is used to decrement the attrition coefficient based on the value of the weight for CC. It is envisioned that as the ability of the friendly forces is hampered by the presence of civilians, the ability of the enemy to engage the friendly units is enhanced. Based on this, some means of obtaining appropriate attrition coefficients without considering civilians is needed and then these coefficients will be adjusted, based on the DM's weight for CC.

1. Attrition Coefficient Determination

To determine the appropriate attrition coefficients, the Bonder-Farrell approach as described by Hartman, Parry, and Caldwell [Ref. 19] is used. In this approach, the attrition coefficient for one force attriting another in direct fire combat (aimed fires) is obtained by determining the expected time for one Y to kill one X. The resulting attrition coefficient then becomes

$$\hat{\alpha}_{ij} = \frac{1}{E[T]}. \tag{5.18}$$

Where T is the time for Y to kill X. In this model, the simple independent repeated shots model is used to develop the attrition coefficients for each side in the scenario. In this case, it is assumed that Blue represents friendly units and Red represents hostile or enemy units. Thereby, the form for the expected time for Blue to kill Red is developed as:

$$E[T] = t_a + \frac{t_s}{P_{ssk}} \tag{5.19}$$

where t_a is the time for one Blue firer to acquire one Red target, t_s is the time to fire one shot, and P_{ssk} is the probability of a single shot kill. Thus, these values are needed to develop the attrition coefficients. It is assumed that P_{ssk} is fixed at 0.7 for Blue and 0.6 for Red. The time to shoot at a target is assumed to be fixed at five seconds. The effect of the civilian presence is captured by varying the time to acquire a target. This assumes that when many civilians are present, the ROE will force the friendly units to spend a significantly longer time to determine if the person they want to engage is a civilian or an enemy soldier. Based on this argument, upper and lower bound values for t_a are established. It is assumed that under ideal conditions, with no civilians present, Blue can acquire a target in ten seconds. Under completely adverse conditions (numerous civilians), Bluc can acquire a target in 60 seconds. From this, the best and worst values for the attntion coefficient of Blue against Red, α_{BR}, are

$$\overline{\alpha}_{BR} = \frac{1}{E[T]} = \frac{1}{10+\left(\frac{.5}{0.7}\right)} = 0.0583 \text{ (best)} \tag{5.20}$$

and

$$\underline{\alpha}_{BR} = \frac{1}{E[T]} = \frac{1}{60+\left(\frac{.5}{0.7}\right)} = 0.0149 \text{ (worst).} \tag{5.21}$$

For Red attriting Blue, there is no penalty for the presence of civilians. However, it is assumed that the Red force can attain, at best, the acquisition and firing times for Blue's soldiers, and, at worst, he will take somewhat longer than Blue to acquire targets, thus the attrition coefficients for Red attriting Blue, α_{RB}, become

$$\overline{\alpha}_{RB} = \frac{1}{E[T]} = \frac{1}{10+\left(\frac{.5}{0.6}\right)} = 0.0546 \text{ (best)} \tag{5.22}$$

and

$$\underline{\alpha}_{RB} = \frac{1}{E[T]} = \frac{1}{30+\left(\frac{.5}{0.6}\right)} = 0.0261 \text{ (worst).} \tag{5.23}$$

In this case, the best attrition coefficient for Red is the unmodified best case when civilians are present and Blue is operating with a very restrictive ROE. Using the weight obtained from the DM for CC, a linear function for the attrition coefficients as a function of w_{CC} is formed. These linear functions are

$$\alpha_{BR}(w_{CC}) = \overline{\alpha}_{BR} - w_{CC}\left(\overline{\alpha}_{BR} - \underline{\alpha}_{BR}\right) \tag{5.24}$$

and

$$\alpha_{RB}(w_{CC}) = \underline{\alpha}_{RB} + w_{CC}\left(\overline{\alpha}_{RB} - \underline{\alpha}_{RB}\right). \tag{5.25}$$

Thus, as the weight for CC increases from zero, Blue's attrition coefficient against Red is decremented and Red's attrition coefficient on Blue is incremented, accordingly. This improvement in Red's attrition rate is due to the increased exposure time for Blue due to the use of his ROE, as measured by w_{cc}.

The attrition coefficient for Blue when using area fires is determined using the methods described by Hartman, Parry, and Caldwell [Ref. 19]. Since Blue is using unaimed fires, the calculation depends only on the lethal area of one round and the area of the entire target. Because Blue will only encounter this situation with no civilians present, there is no modification of this attrition coefficient. Assuming that a man, when fully exposed, reveals a two square meter target, and that the target area is 10,000 square meters, the area fire attrition coefficient becomes

$$\beta_{RB} = \frac{LethalArea}{TotalArea} = \frac{2}{10000} = .0002. \tag{5.26}$$

This coefficient is multiplied by the number of targets in the engagement area to determine the final coefficient used.

To determine the attrition for civilians who happen to be caught in the combat zone, a linear function in w_{cc} is formed, as before. For the lowest attrition rate for Blue against civilians, the lowest attrition rate for Blue is used and then reduced as a function of the fraction of civilians present in the engagement area (node). Thus, the lowest attrition rate for Blue against civilians becomes

$$\underline{\alpha}_{BC} = \lambda \underline{\alpha}_{BR} \text{ where } \lambda = \frac{Civilians}{TotalPopulation}. \tag{5.27}$$

The maximum attrition rate for Blue against civilians is taken to be the largest attrition coefficient for Blue against Red, given as

$$\overline{\alpha}_{BC} = \overline{\alpha}_{BR}. \tag{5.28}$$

Forming a linear function for the attrition coefficient of Blue against civilians yields

$$\alpha_{BC}(w_{CC}) = \overline{\alpha}_{BC} - w_{CC}\left(\overline{\alpha}_{BC} - \underline{\alpha}_{BC}\right). \tag{5.29}$$

Substituting the appropriate values into the above equations produces the final form of the attrition coefficient as

$$\alpha_{BC}(w_{CC}) = \overline{\alpha}_{BR} - w_{CC}\left(\overline{\alpha}_{BR} - \lambda\underline{\alpha}_{BR}\right). \tag{5.30}$$

To calculate the attrition for civilians in a combat scenario, they are treated as participating as targets only, and the Logarithmic Law form of Lanchester's equations is used. This leads to the attrition of civilians being represented as

$$\frac{dc}{dt} = -\alpha_{BC}\, c. \tag{5.31}$$

Now, the range of values for attrition coefficients for each side involved in combat have been determined, as well as the method for determining civilian combat casualties.

2. Civilian Attrition Due to Lack of Aid

To determine the attrition of civilians due to starvation, an attrition coefficient that is a function of the days of supply on hand is used. The basic form of the attrition is given as

$$\frac{dC}{dt} = -d(DOS)C \tag{5.32}$$

where DOS is days of supply on hand, and the function d(DOS) is a linear function,

$$d(DOS) = 0.005 - 0.005DOS,\ 0 \le DOS \le 1. \tag{5.33}$$

Thus, the civilians begin to be attrited due to lack of food and medical aid when they have less than one DOS on hand, and at a maximum rate of 5 per thousand. For example, a civilian population of 10,000 with 0.5 DOS would lose 25 people due to lack of aid and would consume their 0.5 DOS. The maximum rate of death was determined by the recent casualty figures obtained from Rwanda where approximately 5000 people died daily out of an estimated population of 1 million. Civilian attrition, of this fashion, only occurs when their DOS level goes below one DOS on hand. When the DOS level reaches zero the civilians are attrited at the maximum rate, 0.005.

3. Combat Attrition

The various engagement types must now be considered in order to determine the types of combat and attrition rules to follow. In high intensity combat operations with direct fire engagements, the Lanchester Square Law has been used extensively to model engagements. Here combat actions are modeled using the Square Law as a basis for determining expected casualties. When no civilians are present, each side attrits using their maximum attrition coefficient. When civilians are present, the attrition coefficients are adjusted as discussed above, and casualties are assessed to Red, Blue, and civilians. From the state equations, it can be shown that in a fight to the finish, for Blue to win the following inequality must hold

$$\frac{X_0}{Y_0} \geq \sqrt{\frac{\alpha_{RB}}{\alpha_{BR}}}\,. \tag{5.34}$$

Thus, if no civilians are present, the maximum attrition coefficients for Red and Blue are used and when civilians are present, the adjusted coefficients for Red and Blue are used, and casualties are also assessed against the civilians.

In modeling the potential combat actions centering around aid deliveries, these actions are modeled as ambushes. The Deitchman's Mixed Law, as described by Lindsay [Ref. 18], has been used as a model for ambushes. The major assumption concerning the use of the Mixed Law concerns the behavior of the ambushed force. In the Mixed Law formulation, the ambushing force uses aimed fires against the ambushed force, while the ambushed force uses area fires against the ambushing force. This implies that the ambushed force is spraying the area where the ambushing force is located. This assumption is satisfactory if no civilians are present. Assuming there are no civilians present, the conditions under which Blue will win, if ambushed by Red is

$$\frac{X_0}{(Y_0)^2} \geq \frac{\alpha_{RB}}{2\beta_{BR}} \tag{5.35}$$

where the attrition coefficients are the maxima for each side. However, if civilians are present the use of the Mixed Law is questionable. In this case, the Square Law is used instead. This would indicate that the ambushed force must exercise restraint and attempt to engage the attacking force while limiting the collateral damage to civilians. In this case, equation (5.34) is used to determine the conditions under which Blue would win. In this instance it is necessary to modify the attrition coefficients, as described above, and assess civilian casualties.

The assessment of civilian casualties in any of the combat scenarios depends on the length of the primary engagement between Red and Blue. Using the state equations and the terminating conditions, it cas be shown that the time to finish a battle, in the square law case, is given by

$$t = \left(\frac{1}{\sqrt{\alpha_{RB} * \alpha_{BR}}}\right) * \ln\left(\frac{Y_0}{Y_{BP}}\right). \tag{5.36}$$

Here, Y_{BP}, is the breakpoint threshold for the Red force. In this model the threshold is assumed to be fixed at 80% of the initial starting force. This means the Red force will break contact when 20% of their force has been attrited. Because the civilians are not likely to remain in a combat area long after the fighting begins, it is assumed that the civilians exposure time will be limited to the first 2.5% of the battle time. Now, the elements are in place to calculate the civilian attrition due to combat action.

The results of the attrition model are used as inputs to the utility function described above. To obtain the expected number of casualties, the estimates for the number of civilians and enemy forces located on a node from the forecast model are used. Then, the appropriate attrition model to use is determined based on the branch of the decision tree being evaluated. The minimal force required for Blue to win is determined by using the winning condition equations described above. Finally, the expected casualties are input to the utility function to determine the payoff for that particular combination of mission and strength level. Once the utility is known at the result nodes on the decision tree, the expected utility can be rolled back, and the optimal COA for that node can be determined. This rollback methodology is described in the next section.

F. DECISION SOLUTION

To obtain the optimal decision for a particular node, systematic expected utility calculations are performed from the result nodes to the origin node (TF). At each terminus of branches on the decision tree, the maximum utility value must be picked from the candidate values to perform subsequent calculations. In addition, the path history associated with that maximal utility value must be identified. By following this procedure, the maximum utility value at the origin node and the path through the decision tree that produced that result are found. The multi-attribute rollback algorithm described by Marshall [Ref. 14] and Kirkwood [Ref. 20 and Ref. 21] is used to produce this solution.

1. All Paths Algorithm

At this point, it is appropriate to introduce several sets and some new notation to help in the development of the algorithm. Let set D(i) be the set of decisions and C(i) be the set of chance outcomes (TF, TA, CA, CF). Furthermore, let $\mathbf{h}_i$ be a state, or history vector that contains a list of nodes (chance or decision) and branches (outcomes or alternatives) that uniquely identify a path leading from the starting node to node i. Since there may be many paths to a given node, a set $H_i = \{\mathbf{h}_i\}$ is associated with each node i. Assuming node i is reached via history $\mathbf{h}_i$, and then follows branch j, that leads to the next node k. Then the state vector at node k is given as $\mathbf{h}_k = [\mathbf{h}_i, (i, j)]$. Thus, each element in the history vector is a pair of numbers in which the first is a node number and the second is a branch number. The following algorithm generates all the path histories in the decision tree (assumes the starting node is numbered as 1) and is as follows:

1. Define a set H_i for each node and set H_i = NULL (Empty Set) for all i.
2. Set $\mathbf{h}_1$ = NULL and $H_1 = \{\mathbf{h}_1\}$.
3. Consider the next higher numbered node. If at node i and $i \in D$, each branch j with $j \in D(i|\mathbf{h}_i)$ leads to a node k. Set $\mathbf{h}_k = [\mathbf{h}_i, (i, j)]$ and add it to H_k.
4. If at node i and $i \in C$, each branch j with $j \in C(i|\mathbf{h}_i)$ leads to a node k. Set $\mathbf{h}_k = [\mathbf{h}_i, (i, j)]$ and add it to H_k.
5. Repeat steps 2 and 3 for all chance and decision nodes to determine the disjoint sets H_i.

The procedure terminates and the union of the H_i sets contains all the paths in the tree. Now, the outcomes can be calculated, and the rollback algorithm can be used to determine the solution to the problem.

2. Resource and Utility Level Determination

To calculate the utility outcome, the levels of each attribute considered in the utility calculation must be determined. Previous discussion has shown how to calculate the attrition values which go into the calculation of friendly casualties, enemy casualties, civilian casualties due to lack of aid, and civilian casualties due to combat. Now, it must be determined how to calculate the amount of aid to deliver in order to produce a utility measure for this attribute.

When it is decided to provide aid to a group of civilians, a delivery of a minimum of seven days of supply to the node is attempted. As a maximum value, transport will include the maximum daily haul tonnage, which is a function of the transportation assets available to the friendly forces. A daily haul capacity of ten tons per vehicle per decision cycle is used. In each case, it will be attempted to provide the maximum aid possible to each node requiring aid. In the event attempts are made to provide aid beyond the capabilities of transportation assets, the aid delivered is reduced to a feasible amount.

The inputs to the utility function for each attribute of interest can now be calculated. From this, the payoff (utility) at each result node in the decision tree can be obtained, and the rollback algorithm can be used to calculate the optimal decision for each node.

3. Rollback Algorithm

Now, consider the situation where the payoff $r_j(\mathbf{h}_i)$ for every branch j leaving node i in the decision tree is some given value. Since every terminal node is at the end of a single branch, it can be assumed that any payoff associated with a terminal node is assigned to that single branch. The objective is to maximize the expected value v_1 at the origin node. The following algorithm finds the optimal paths, decisions, and returns.

1. Label all terminal nodes at the end of every path with 0; this means setting $v_i(\mathbf{h}_i) = 0$ for every $\mathbf{h}_i$ in H_i.
2. Find an unlabeled node i where all later occurring nodes k connected to it are labeled.
   (a) If $i \in D$ set $v_i(\mathbf{h}_i) = \underset{j \in D_i(\mathbf{h}_i)}{Max} \{r_j(\mathbf{h}_i) + v_k(\mathbf{h}_k)\}$ and d^* equal to the j that yields this

maximum

(b) if $i \in C$ set $v_i(\mathbf{h}_i) = \sum_{j \in D(i|\mathbf{h}_i)} p_j(\mathbf{h}_i)[r_j(\mathbf{h}_i) + v_k(\mathbf{h}_k)]$.

Step 2 is repeated until the starting node is labeled. The starting node label gives the maximum expected utility for the problem and the d^*'s computed at each decision node give the optimal decisions. To aid in the formulation of this problem, the data for the decision trees are collected in Appendix D.

Now, the basis for producing an algorithm to calculate the maximum expected utility for each node, and the decisions that were used to obtain that utility value have been developed. In addition, the required resources to accomplish the mission are also known. This procedure can be iterated over all nodes to determine the optimal COA for each node and the resources required to accomplish this goal. From this it is possible to form a theater wide strategy that maximizes total utility and achieve the theater goals.

G. THEATER COURSE OF ACTION DEVELOPMENT

Now that the optimal COAs are known for each node, these nodes can be ordered by the utility value associated with the COA. By applying resource constraints, it can then be determined which COAs are possible to execute in any given decision cycle. Any remaining resources are held in reserve and are available for future use. The COAs that are resourced can be executed and the results of these actions observed.

Once the results of a set of COAs are known, the forecasts can be appropriately updated, and start the planning cycle anew. From this methodology, answers to the questions of how to develop a theater-wide COA with constrained resources has been found. The method began by establishing the forecasts for the threat and civilian needs at a node through the use of probability forecasts. The number of civilians and enemy at the nodes were then estimated. Attrition models were used to determine the expected number of casualties for a given set of decisions at a node. The utility associated with each result node in the decision tree was then calculated, and the history algorithm was used to determine all the possible paths in the decision tree. The rollback algorithm determined the optimal utility return, and the decisions associated with that value. The node COAs were ranked by the utility values obtained, and those COAs within resource limitations were executed. Finally, the world state and the forecasts were updated, as required. The source code for the model can be obtained by writing Professor Parry at the following address:

> Professor Samual Parry
> Operations Research Department
> ATTN: Code OR/Py
> Naval Postgraduate School
> Monterey, California 93943

The model was written in Borland's Turbo Pascal for Windows^{c} version 1.5 and is a Windows 3.1^{c} application. It easily runs on any personal computer with a functional Windows 3.1^{c} environment. An example of the model output can be found at Appendix D.

VI. MODEL ANALYSIS

A. METHODOLOGY

The analysis of the model will be conducted using a two phased approach. The first phase will use a series of one decision cycle runs with perturbation of input parameters to evaluate the impact of these parameters. The second phase will use a series of longer runs, 10 to 100 decision cycles, to evaluate the long run effect of the input parameters on decision making. The ending conditions for the longer runs are: all nodes with civilians have the days of supply (DOS) level specified for the theater, all friendly troops killed, or all friendly trucks destroyed. The specified DOS level for the tests will be 30 DOS. This means the theater goal is for each node with civilians to have 30 DOS on hand at the end of a decision cycle to end the simulation.

B. RESULTS

The model was run for ten replications of 100 decision cycles using two different DM "personalities" to determine the capabilities of the model. The "personalities" used were the humanitarian and aggressive commanders. The humanitarian commander was primarily interested in distributing aid while minimizing friendly and civilian casualties. The aggressive commander was primarily concerned with killing the enemy. The weights used for the attributes for these DM cases are shown in Table 6.1. For each commander type, there were two initial resource states considered; one with limited resources and one with ample resources. In the ample resources case, the initial forces were 10,000 troops and 100 trucks. In the limited resources case, there were 1000 troops and 10 trucks. The initial conditions for the world were the same for each model run. These initial conditions can be found in Table 6.2.

1. General

In no instance was the model able to satisfy the termination condition for aid when the standard input parameters were used. As a result, the model either stopped due to the time or resource constraint being invoked. When the aggressive DM was used, the simulation terminated within 38 decision cycles because of friendly casualties. When the humanitarian DM was used, the simulation terminated within 72 decision cycles due to loss of vehicles. In every instance the humanitarian DM reached an equilibrium state, in

Attributes	Humanitarian Commander	Aggressive Commander
Friendly Casualties (FC)	0.44388	0.40698
Enemy Casualties (EC)	0.04073	0.40019
Civilian Casualties due to Combat (CC)	0.2469	0.0437
Civilian Casualties due to Lack of Aid (CA)	0.15254	0.04733
Aid Delivered (AD)	0.11595	0.1018

Table 6.1. Decision Maker's Attribute Weights

Node	Number of Civilians	Number of Enemy	DOS On Hand
One	10,000	100	0.1
Two	10,000	1,000	0.1
Three	10,000	100	20
Four	10,000	1,000	20
Five	100,000	100	0.1
Six	100,000	1,000	0.1
Seven	100,000	100	20
Eight	100,000	1,000	20
Nine	50,000	500	20
Ten	50,000	500	8

Table 6.2. Initial World State

terms of civilian casualties, much sooner than the aggressive commander. The casualty rates for each decision maker during the simulation are shown in Figures 6.1 through 6.4.

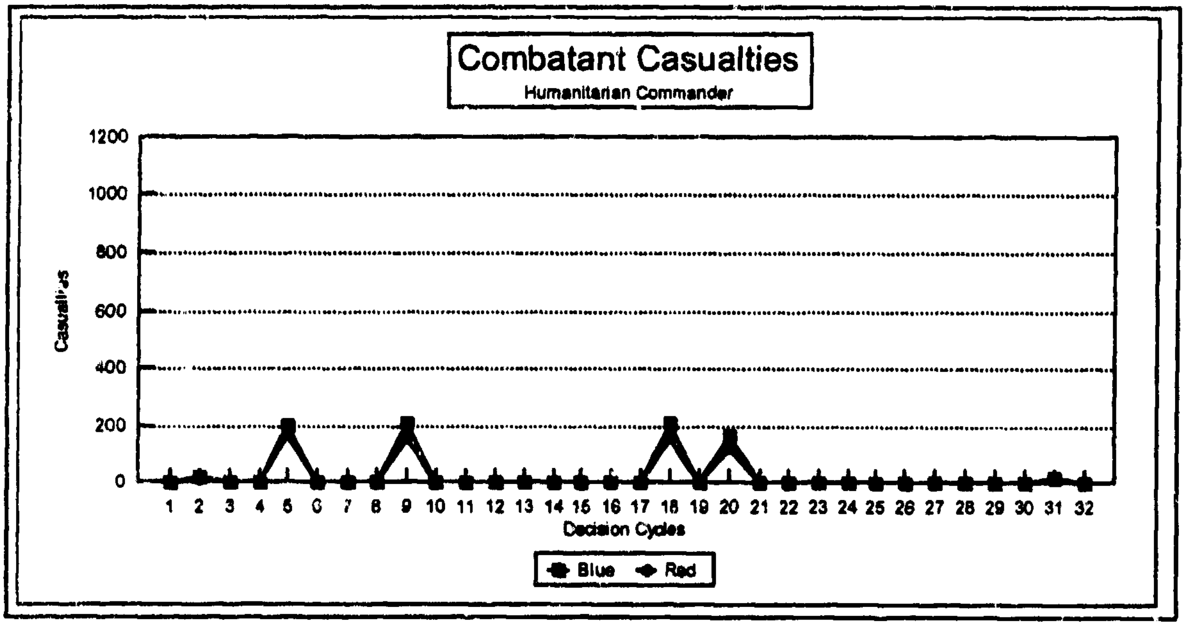

Figure 6.1. Humanitarian Commander Combatant Casualties

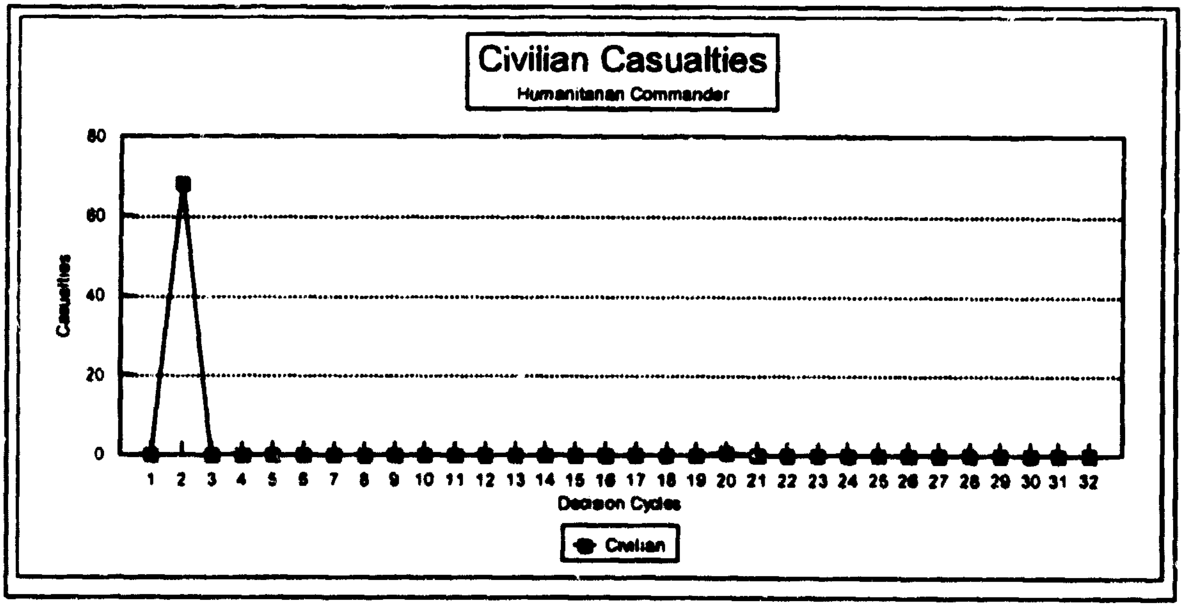

Figure 6.2. Humanitarian Commander Civilian Casualties

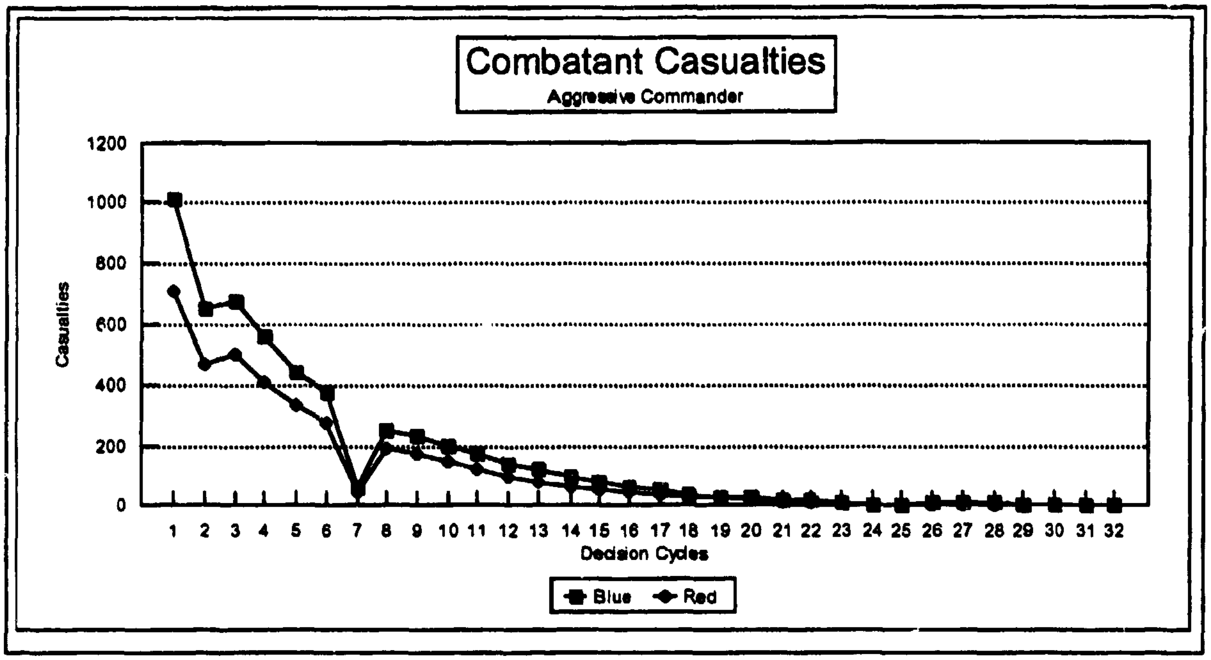

Figure 6.3. Aggressive Commander Combatant Casualties

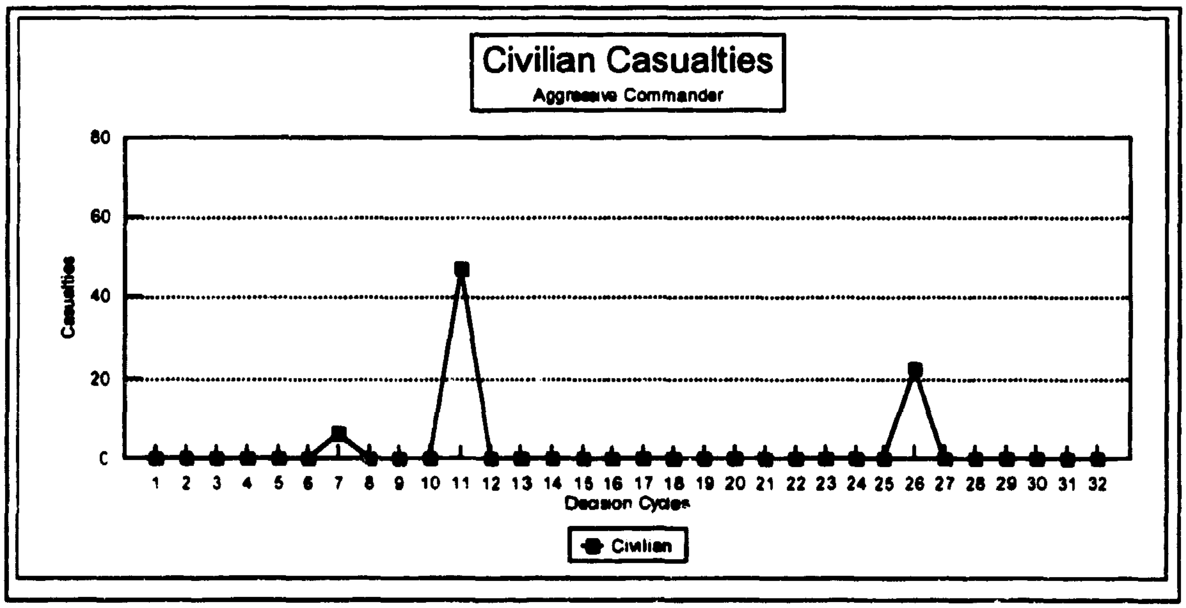

Figure 6.4. Aggressive Commander Civilian Casualties

These figures show the effect of employing the DM types in the ample resources case. Notice that the humanitarian commander was able to reach a steady state, in terms of civilian casualties, much sooner than the aggressive commander, and that the civilian casualties were reduced to a much lower level by the humanitarian commander. An interesting point is that the aggressive commander chose to aid certain nodes early during the run but primarily focused on combat thereafter.

The spikes of casualties seen on the humanitarian commander graphs are a result of ambushes carried out by enemy forces on certain nodes. Notice that the spikes for combatant losses on Figures 6.1 are much lower than those depicted in Figure 6.3. This evidences the fact that the humanitarian commander only fought when he was attacked. Also, note that the overall rate of civilian casualties is very low when compared to the aggressive commander (Figure 6.2 versus Figure 6.4). It is interesting to note that the humanitarian commander never chose to resort to combat except in self-defense, while the aggressive commander only occasionally performed the aid mission.

The aggressive commander graphs clearly show the primary intent of this commander, to kill the enemy. The smooth descent of combatant casualties and concurrently high civilian casualty rate are a direct result of his priority in that area. The occasional dips in civilian casualties are a result of the aggressive commander choosing to aid the civilians at certain points during the run. The primary cause for the decrease in civilian casualties over the run was due to their attrition suffered, which reduced the civilian population available for attrition the next decision cycle.

One particular limitation of the model is pointed out by these results; the influence of the DM type and the associated utility structure are so strong that the effects of the forecasting model are apparently overwhelmed. For example, early in the runs the aggressive commander chose to aid the civilians at certain nodes as shown in Figure 6.3 by the dips for combatant casualties at decision cycles two and seven. Later when the aggressive commander eliminated the opposing forces, he made no attempt to reduce the civilian casualties by delivering aid until the available troops for combat strength was very low, four. This was due to the low weights associated with civilian casualties by this DM. The impact of the civilian aid forecast probabilities going toward one, more critical, was not strong enough to cause the model to begin to aid the civilians. This type result is shown in Figure 6.5.

===== Node =====	
Node = Six	DOS Delivered 0.00
DOS = 0.00	Utility 0.6638
Perc DOS = 0.17	Trucks Used 0
Perc Civilian = 68531	Troops Used 2
Perc Enemy = 3	Blue Losses 0
COA = Combat	Red Losses 0
Executed = TRUE	Civilian Losses 483
Outcome = Blue Wins	Vehicle Losses 0
--- Decision Probs ---	--- Decision Probs ---
Critical 1.0000	Hostile 0.0704
Poss Critical 0.6667	Poss Hostile 0.0694
Not Critical 0.5000	Not Hostile 0.0563

Figure 6.5. Sample Output Showing Preference Overpowering Forecast

2. Forecasts

The forecasts were tested by allowing the model to run for a long time, 100 decision cycles, and observing the effect of the growing sample size in the forecast. To observe the effect of changing the variance of the strength estimate, the parameter was varied over a range of values and changes in outcomes were collected. The assessment of the impact of these values hinges on demonstrating cases where the number of samples in a forecast caused problems in producing realistic output and on determining the value where the variance changes the COA decision.

a. Forecast Sample Size

The forecast sample size did not impact on the predictive power of the civilian aid requirements forecast, due to the updating scheme used. However, the threat forecast did not use a multi-step update and tended to become very heavily weighted toward the prior distribution when the sample size grew much over 50. At that point, the forecast was insensitive to any input which contradicted the prior distribution. This was most evident during the latter portion, after 50 decision cycles, of the long runs. In most instances, the probability values in the civilian aid requirements forecasts tended to move in response to the changing world state. The only exception, as discussed above, was when the aggressive commander ignored the needs of the civilians for so long that the prior distribution was firmly biased toward critical need. However, in this instance it was appropriate for the forecast to be heavily biased.

b. Strength Estimate Variance

The strength estimate variance produced the expected result of reducing the average number of casualties taken to accomplish the mission. The variance parameter, a fractional portion of the mean used as variance size, was changed from 0 to 1 in increments of 0.1. When the parameter is set at 0, the model produces completely correct sensor reports and when set to 1, the reports are very error prone. As the variance parameter was reduced toward 0.1, meaning that the variance is 10% of the mean, the accuracy of the strength values and DOS needed became increasingly accurate. This allowed the resource module to more accurately predict what resources were required to achieve the mission. When a fight occurred, blue was more likely to win the battle due to the improved accuracy of the enemy strength estimate. This was clearly shown when the humanitarian commander successfully completed the mission in 40 decision cycles when the variance was set at 10% of the mean. The values between 0.2 and 0.8 provided similar results in terms of casualties over time. At the extreme ends of the scale used, the results were significant enough to change the outcome of the model runs. This result is shown graphically in Figure 6.6.

3. Utility Function Parameters

The utility function parameters evaluated are the attribute weights and the β values for the individual attribute utility functions. In evaluating the weights, the β values were held constant at two and during the β value testing, the weights were held constant at 0.2. In each experiment, one model run was made for a decision cycle to evaluate the impact of the parameter change. A common random number seed was used for each run to duplicate the random effects between model runs.

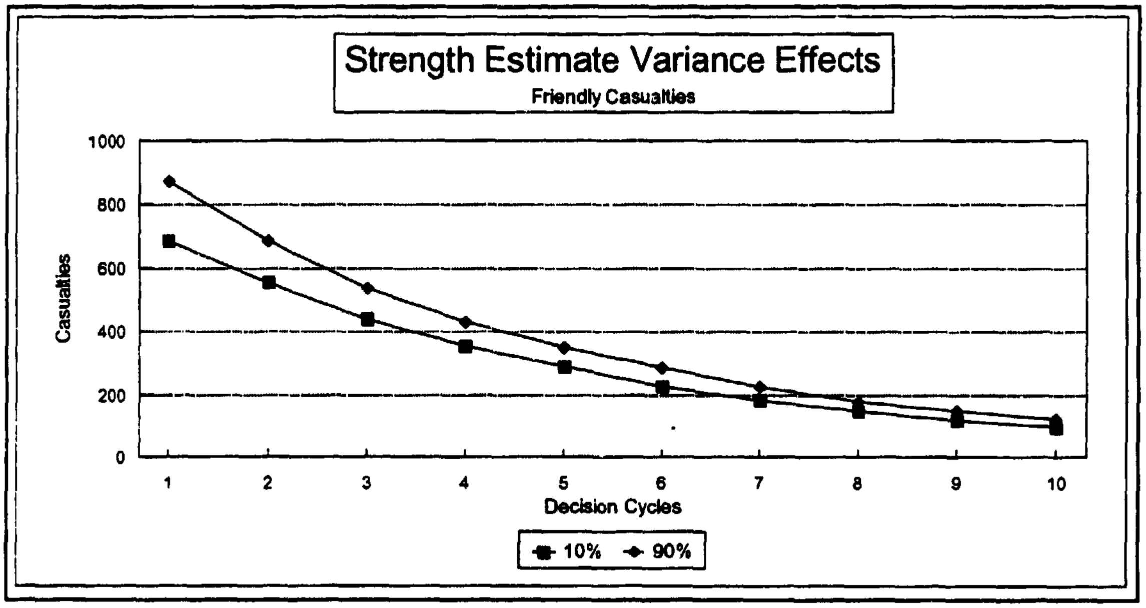

Figure 6.6. Effect Of Variance Change On Friendly Casualties

a. Attribute Weights

The attribute weights were perturbed over the range 0 to 1 in steps of 0.01. The evaluation method consisted of setting the weight of the attribute of interest and then dividing the remaining weight equally among the remaining attributes. Finally, the combinations of associated weights were considered to evaluate the effect of combinations of weights. For example, the weights for civilian casualties are set to certain levels to determine the synergistic effect of that combination. Due to the large number of combinations possible, only selected combinations were explored. The results of this analysis are shown in Table 6.3.

The friendly casualty weight was found to exhibit a strong tendency toward selecting the Combat COA when set lower than 0.36 and toward selecting the Aid COA when set higher than 0.36. Interestingly, when set at 0.36 the model chose a mixed strategy of the Combat and Aid COAs. The enemy casualties weight was found to exhibit a strong tendency toward selecting the Aid COA when below 0.1 and toward selecting the Combat COA when set above 0.1. As in the case of the friendly casualties weight, the enemy casualties weight exhibited a tendency to select a mixed strategy when set at 0.1.

Attribute	COA		
	Combat	Aid	Mixed
Friendly Casualties (FC)	< 0.36	> 0.36	0.36
Enemy Casualties (EC)	> 0.1	< 0.1	0.1
Civilian Casualties due to Combat (CC)	< 0.94	> 0.94	0.94
Civilian Casualties due to Lack of Aid (CA)	< 1.0	= 1.0	NA
Aid Delivered (AD)	< 1.0	= 1.0	NA

Table 6.3. Attribute Weights Breakpoints For Coa Selection

The civilian casualties due to combat weight was found to exhibit a strong tendency toward selecting the Combat COA when set below 0.94 and toward selecting the Aid COA when set higher than 0.94. Again, the civilian casualties due to combat weight exhibited a mixed strategy when set at 0.94. The civilian casualties due to lack of aid weight was found to exhibit a strong tendency toward selecting the Combat COA when set below 1.0 and toward selecting the Aid COA when set at 1.0. This is due to the strong influence of the other parameter values toward the Combat COA. The aid delivered weight was found to exhibit a strong tendency toward selecting the Combat COA when set below 1.0 and toward selecting the Aid COA when set at 1.0. Again, the impact of the other parameters toward the Combat COA are too severe to overcome until they are set to zero.

Comparisons of associated weights consisted of three tests. The first produced a set of weights for civilian casualties and distributing the remaining weight equally among the remaining attributes. The second produced weights for enemy and friendly casualties and distributed the remainder to the other attributes. While the third produced a weight for civilian casualties and aid delivery with the remaining weight distributed to the other attributes.

In the first test, when the weights for civilian casualties, w_{CC} and w_{CA}, were set at a combined weight higher than 0.96, the result was a consistent decision to choose the Aid COA. When the weights were set equal or less than 0.96, the decision was the Combat COA. This result is consistent with the result obtained in the single weight effects experiment.

In the second test, if the combined weights of w_{FC} and w_{EC} were set greater than 0.1, the result was a unanimous decision for the Combat COA. If the combined weights were set less than 0.1, the decision was in favor of the Aid COA. Again, if the combined weights were set to 0.1, the result was a mixed strategy. This result agrees with the expected results as indicated by the single weight effects experiment.

In the third test, if the combined weights of w_{CC}, w_{CA}, and w_{AD} were set lower than 0.33, the result was the Combat COA. If set to 0.33 or higher, the result was to choose the Aid COA. This result is entirely consistent with the second multiple weight change experiment. These results of this analysis are presented in Table 6.4.

Attribute	COA		
	Combat	Aid	Mixed
CC & CA	< 0.96	> 0.96	NA
FC & EC	> 0.01	< 0.01	0.01
CC, CA, & AD	< 0.33	> 0.33	NA

Table 6.4. Multiple Weight Impacts On Course Of Action Decision

b. β Values

To test the impact of the β values, they were systematically varied from 2 to a large number (9.9E30). The steps used were 2, 10, 100, 1000, and 9.9E30. In every instance the decisions were not impacted by changing the values of the β's. The decision was consistent with the distribution of the attribute weights as noted above and remained fixed no matter what level of β was used. Thus, the model is insensitive to the level of β used.

C. APPLICATION TO SOMALIA DATA

Once the parameter testing was completed, the model was run using the data, which is representative of Somalia, from Appendices A and B. The results of these runs were very interesting. The humanitarian commander was able to quickly, within 45 decision cycles, reduce the civilian casualties to a very low level, but it took him 277 decision cycles to complete the mission. On the other hand, the aggressive commander was able to subdue the enemy forces within the first 30 decision cycles, but was unable to reduce the civilian casualty rate much below 200. The aggressive commander was unable to complete the mission because of the high number of losses he sustained in the initial combat reduced his ability to deliver aid. The insight gained through this cursory examination of a sample scenario is beneficial in assisting the investigation of the dynamic effect of mission priorities over a long planning horizon. From this analysis, it would appear that the best overall plan for an OOTW mission would be to establish a goal of providing the most humanitarian assistance possible early in the operation, and have a strong reaction force to retaliate for any attacks made against our forces. This would combine the best outcomes from each of the notional commander types by reducing the civilian casualty rate quickly, while simultaneously providing a strong deterrent against any potential attacks. The casualty data for these model runs are shown in Figures 6.7 and 6.8 and a comparison of the first 30 decision cycles' aid delivery rates is shown in Figure 6.9. Note that the Y-axis scales are different on Figures 6.7 and 6.8.

D. CONCLUSIONS

The results of the model runs were adequate for a simple decision model using very crude sensors. However, the model did tend to produce some unexpected results as a result of the utility model construction. The model was not as sensitive to the forecasts as it needed to be and, as a result, the utility weights seemed to be the parameters that drove the decision model to pick the COA for each node. Only occasionally, when the need for aid was very desperate and the numbers of civilians on the node quite large, did

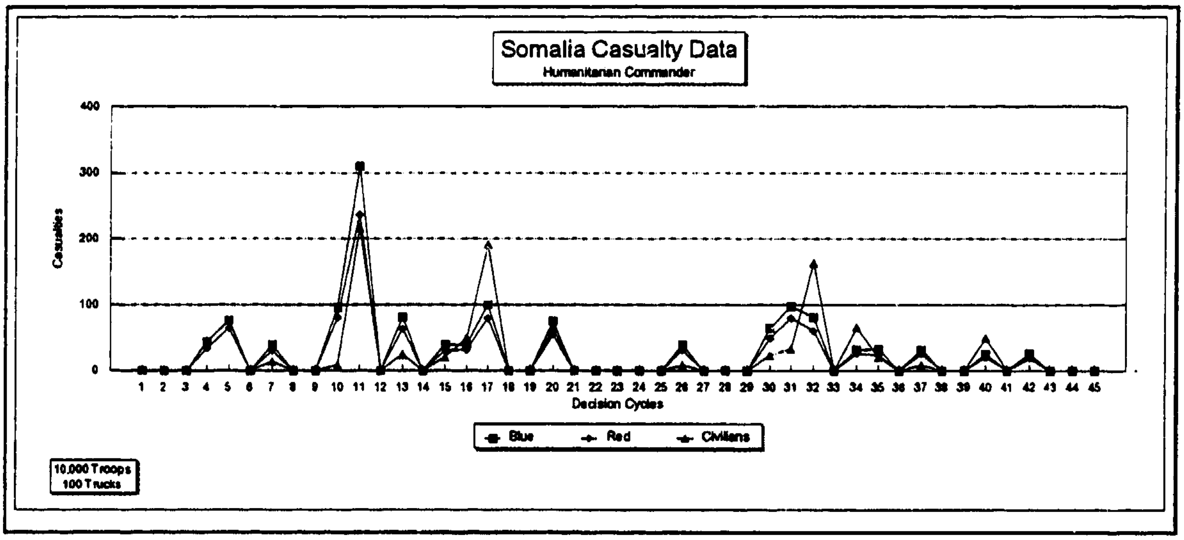

Figure 6.7. Casualty Trends For Somalia (Humanitarian Commander)

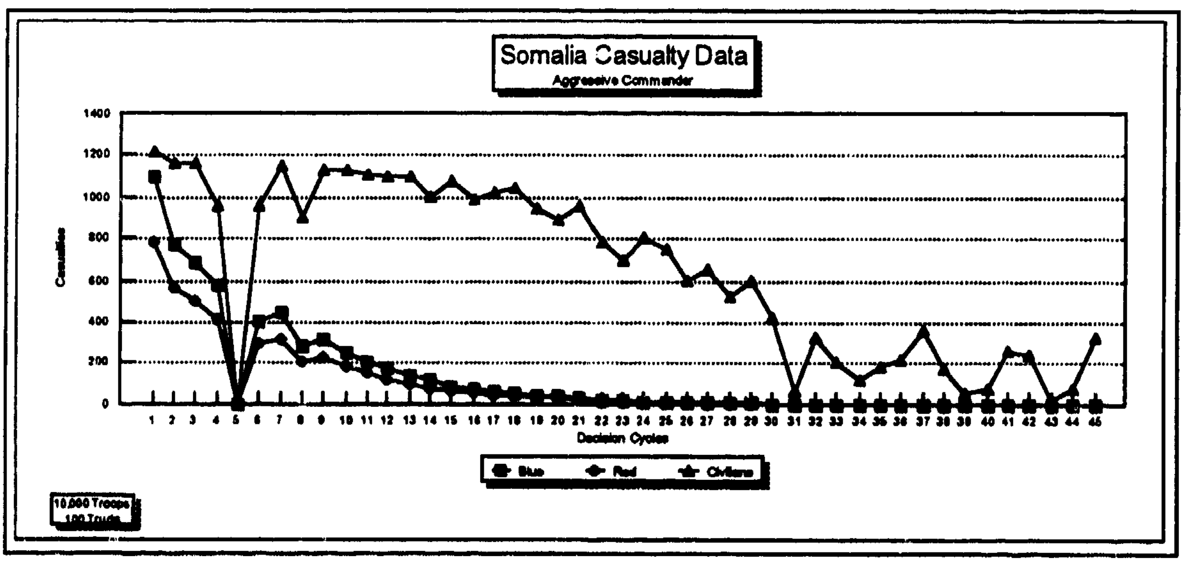

Figure 6.8. Casualty Trends For Somalia (Aggressive Commander)

the aggressive commander chose to aid a node while he had a large combat capability. In general, his preference toward combat drove him to attack until his ability to continue the fight was nonexistent, and then attempt to aid the civilians. At that point, any residual enemy forces could easily defeat his force and win the campaign. The most surprising result was the insensitivity of the utility model to the β values. This is more evidence for the overall conclusion that the model is really driven by the attribute weights; in particular, the weights for friendly and enemy casualties.

Overall, the model results were believable given the quality of the forecasted information. In the analysis of the Somalia data, the model produced some insights into the interaction of priorities within this type operation. It was quite easy to observe the model results and draw appropriate cause and effect conclusions from the output. The casualty data are but one form of output available. The most informative data concerning the decision making history are the node decision information as shown in Figure 6.5. These data provide significant insights into the decision making process over time.

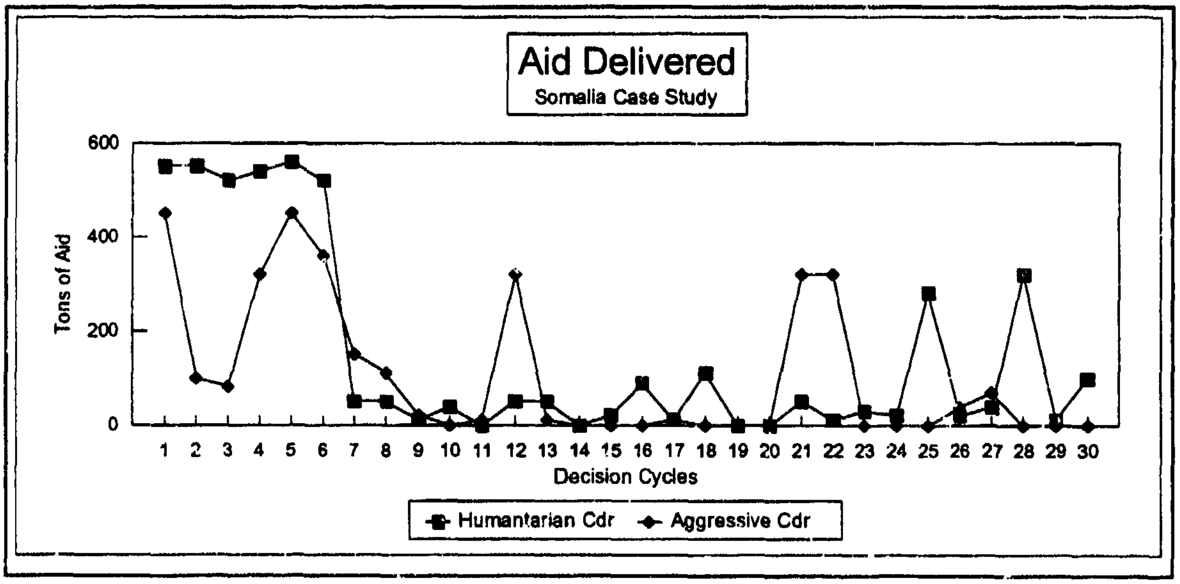

Figure 6.9. Aid Delivery Rates

E. FUTURE WORK

1. Forecasts

The forecast model needs to be improved through the addition of more realistic sensors for strength and composition values. This sensor model should be directly related to actual sensor platforms in use in the OOTW environment. The probability forecast could be enhanced by revising the updating scheme for the threat forecast as a minimum. However, using a belief network approach would lead to a stronger formulation with better connections to the sensor model. In this approach, the variables that affect the determination of the threat probability vector could be linked together in a directed acyclic graph. The evidence collected by the sensor model could then be inserted into this structure which would then propagate through the network producing a new probability vector. These improvements to the sensor model should enhance the face validity of the model and produce more realistic results.

2. Utility Model

Improvements to the utility model must include the development of a more sophisticated utility function form. The inclusion of a larger, more representative sample, of attributes would be an excellent starting point. In addition, some form of penalty for making a decision which results in a catastrophic failure should be included. This would enforce a more averse decision making policy. As a result, the aggressive decision maker would be forced to reduce his combat actions after sustaining a large loss in the field. Further study to find the best form of utility function should be done. The logarithmic form is suitable as a first approximation; however, there is a need for a convex function to represent those attributes with very high utility values at one end of the scale and rapidly decreasing values across the scale. The logarithmic form can only approximate a straight line at one extreme and a severely concave function at the other.

3. Decision Model

The decision model could benefit by the inclusion of more forecast inputs and additional COAs. The most critical and obvious choices were used to construct this model. Improvements could easily be made through the use of additional forecasts such as the host nation support forecast, or the allies support forecast to predict the popularity, and hence, support from these players for the chosen COA. The addition of more depth to the decisions available to the DM would add to the realism of the model. For example, the DM could make the decision to use sensors to collect more information from a node before committing to any COA at that node. He could decide to employ a ruse or decoy operation in an attempt to deceive the enemy forces, or he could decide to employ other humanitarian or special purpose units in other specialized roles. All these additions could be incorporated within the basic framework of the decision tree structure. The rollback algorithm, as encoded, is well suited to solving problems in excess of one million endpoints. The addition of continuous random variables within the decision tree would also tend to smooth the response of the model to changing sensor and world state inputs.

4. Attrition Model

The attrition model could be improved by modifying the civilian attrition model used to capture the effect of civilians in the engagement area. The current model produces an increasing number of casualties based on the number of civilians on the node. Because the node can represent a very large space, it is unrealistic to expect that all the civilians are candidates for attrition if there is an ambush in the node. Further improvements could be made by incorporating indirect fire attrition, including civilians, and aircraft munitions attrition. This would allow the modeling of a wide range of weapon systems.

5. COA Generation

The generation of the theater level COAs could be improved by performing an optimization over some uncertain planning horizon. The optimization could take into account the uncertainty of the success of the current COAs and make provisions for failing to achieve the current goals. The main point here is that it does not always make sense to commit every available resource every decision cycle. This is somewhat unrealistic, if the planning cycle is short, and can lead to catastrophic results when the current COAs are unsuccessful.

Future work in developing this model for decision making could produce a very realistic and accurate portrait of the issues and factors to consider in the OOTW environment. The enhancements discussed would greatly improve the face validity of the model and add a large amount of realism to the product.

APPENDIX A. NODE-ARC REPRESENTATION

A. INTRODUCTION

The data contained in this appendix are estimates from map reconnaissance and what information is available on this subject. Figure A.1 shows an near-scale drawing of the area of interest in Somalia. Close nodes are exaggerated for clarity.

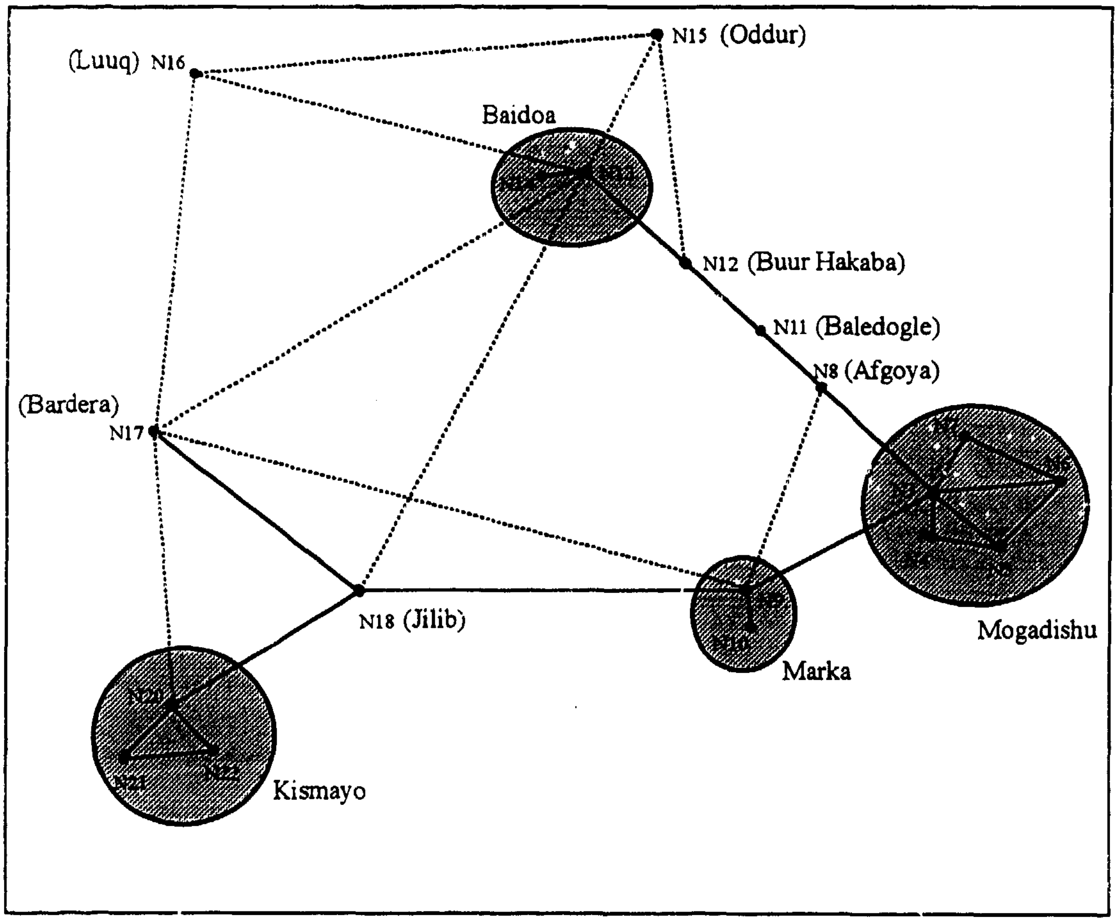

Figure A.1. Node-Arc Network Of Somalia

B. NODE DESCRIPTIONS AND ATTRIBUTES

The physical nodes needed for the Somalia model are listed in Table A.1. The definitions of the attributes needed are as follows:

- Node = An arbitrary ID number for each node
- Name = Name of town at node.
- Size = Diameter of node in KM.
- Location = (X,Y) coordinate on an arbitrary 35x35 grid.

This is used to assist in creating a scale map and to interface with the air grid. The grid origin is in the lower left corner.

Node #	Name	Size	Location
N3	Mogadishu-K4 circle	3	21,18
N4	Mogadishu-Airport	2	20,16
N5	Mogadishu-Seaport	2	22,16
N6	Mogadishu-East	2	23,18
N7	Mogadishu-North	2	21,20
N8	Afgoye	1	18,19
N9	Marka	2	17,15
N10	Marka-Seaport	1	17,14
N11	Baledogle	3	15,20
N12	Buur Hakaba	2	12,22
N13	Baidoa	3	10,24
N14	Baidoa-Airport	1	9,24
N15	Oddur	2	12,31
N16	Luuq	1	3,29
N17	Bardera	2	1,20
N18	Jilib	1	4,8
N20	Kismayo	3	2,2
N21	Kismayo-Airport	2	1,1
N22	Kismayo-Seaport	1	3,1

Table A.1. Node Attributes

C. ARC ATTRIBUTES

The arcs needed to build a model of Somalia are listed in Table A.2. The arc attributes needed to constructed the model are as follows:

- Arc = An arbitrary ID number for each arc.
- Nodes = The terminus of each end of the corridor.
- Cap = Capacity of mobility corridor, by unit size (Width).

- Roads = Scale of number and quality of roads in corridor.
- Terrain = Terrain type (open, hills, forest, urban, sea, etc.).
- Cover = Aggregated % of cover across the arc.
- Obstacles = Aggregated % of obstacles on arc.
- Distance = Length of arc from node to node (KM).

Arc	Nodes		Capacity	Roads	Terrain	Cover	Obstacles	Distance
	Head	Tail						
A1	N3	N4	CO	2	Urban	.7	.05	1
A2	N4	N5	'	2	'	.7	.05	1
A3	N3	N5	'	3	'	.7	.05	1
A4	N5	N6	'	3	'	.7	.05	1
A5	N3	N7	'	3	'	.7	.05	1
A6	N6	N7	'	3	'	.7	.05	1
A7	N3	N6	'	3	'	.7	.05	1
A8	N3	N9	BDE	2	Open	.05	.05	90
A9	N9	N10	CO	2	Urban	.35	.05	1
A10	N9	N18	BDE	2	Open	.05	.05	290
A11	N18	N20	BDE	2	Open	.05	.05	110
A13	N20	N22	CO	2	Urban	.40	.05	1
A14	N22	N21	CO	2	'	.45	.05	1
A15	N21	N20	CO	2	'	.45	.05	1
A16	N18	N17	BDE	2	Open	.08	.05	300
A17	N17	N13	BDE	1	Open	.05	.05	170
A18	N13	N14	CO	2	Urban	.55	.05	1
A19	N16	N13	BN	1	Open	.05	.05	150
A20	N16	N15	'	1	'	.05	.05	150
A21	N15	N13	'	1	'	.05	.05	150
A22	N13	N12	BDE	2	'	.05	.05	90
A23	N12	N11	BDE	2	'	.05	.05	80
A24	N11	N8	BN	2	'	.08	.15	20
A25	N8	N3	BN	2	'	.08	.15	70
A26	N20	N17	CO	0	'	.10	.25	500
A27	N17	N16	BN	1	Hill	.15	.10	150
A28	N15	N12	'	0	Open	.20	.25	240
A29	N17	N9	'	0	'	.05	.25	350
A30	N9	N8	'	1	'	.05	.05	70
A31	N13	N18	'	0	'	.05	.25	400

Table A.2. Arc Attributes.

APPENDIX B. DISPOSITION OF FORCES

The following disposition of forces is for the civilian populace, the clans, and the U.S.. The index numbers shown are for reference only and have no impact on play. The GREEN Force, shown in Table B.1, represents the civilian population that is friendly to the Aideed clan. The RED Force, shown in Table B.2, represents the Aideed clan that are under arms and organized for combat against the U.S. The WHITE Force, shown in Table B.3, represents the civilian population that is somewhat friendly or neutral to the U.S. player. The BLUE Force represents the U.S. Forces available for deployment to theater and are therefore not located on a node within Somalia.

The personnel counts shown are only estimates based on admittedly sparse information. It is believed that the provided information is accurate enough to test the principle foci of the modeling effort. Before any attempt at validity is done, better estimates of forces and asset counts should be collected.

Index #	Assets	Unit type	Location
1	20,000 personnel	Civilian	N3
2	5,000 personnel	Civil	N4
3	500 personnel	Civil	N5
4	20,000 personnel	Civil	N6
5	20,000 personnel	Civil	N7
6	3,000 personnel	Civil	N8
7	10,000 personnel	Civil	N9
8	2,000 personnel	Civil	N10
9	1,000 personnel	Civil	N18
10	1,000 personnel	Civil	N20
11	1,000 personnel	Civil	N21
12	2,000 personnel	Civil	N22
13	1,000 personnel	Civil	N11
14	1,000 personnel	Civil	N12
15	500 personnel	Civil	N17

Table B.1. Aideed Supporters (Green Force) Disposition

Index #	Assets	Unit type	Location
1	1,000 personnel	Militia	N3
2	200 personnel	Militia	N4
3	500 personnel	Militia	N5
4	500 personnel	Militia	N6
5	500 personnel	Militia	N7
6	500 personnel	Militia	N8
7	500 personnel	Militia	N9
8	500 personnel	Militia	N10
9	200 personnel	Militia	N18
10	500 personnel	Militia	N20
11	200 personnel	Militia	N21
12	200 personnel	Militia	N22
13	200 personnel	Militia	N11
14	200 personnel	Militia	N12
15	200 personnel	Militia	N17

Table B.2. Aideed Clan (Red Force) Disposition

Index #	Assets	Unit type	Location
1	3000 personnel	Civilian	N3
2	3000 personnel	Civil	N4
3	3000 personnel	Civil	N5
4	3000 personnel	Civil	N6
5	3000 personnel	Civil	N7
6	3000 personnel	Civil	N20
7	1000 personnel	Civil	N8
8	1000 personnel	Civil	N9
9	1000 personnel	Civil	N10
10	1000 personnel	Civil	N21
11	1000 personnel	Civil	N22
12	5000 personnel	Civil	N13
13	5000 personnel	Civil	N14
14	5000 personnel	Civil	N17
15	5000 personnel	Civil	N16
16	5000 personnel	Civil	N15
17	5000 personnel	Civil	N13
18	5000 personnel	Civil	N12
19	5000 personnel	Civil	N11
20	5000 personnel	Civil	N17

Table B.3. Neutrals (White Force) Disposition

APPENDIX C. UTILITY FUNCTION CURVES

Sample graphs of utility functions for each attribute.

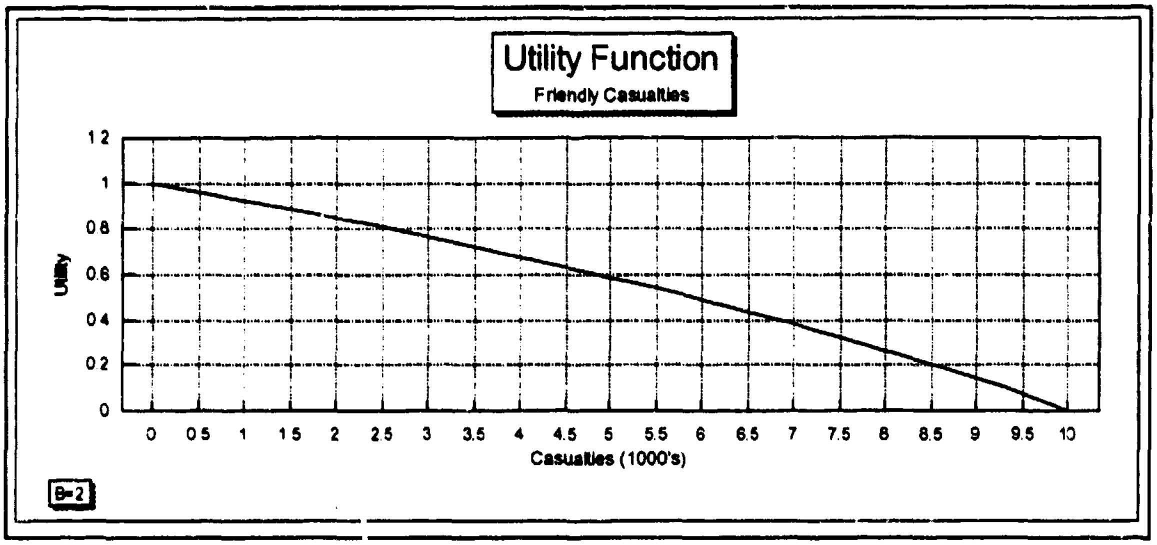

Figure C.1. Friendly Casualties

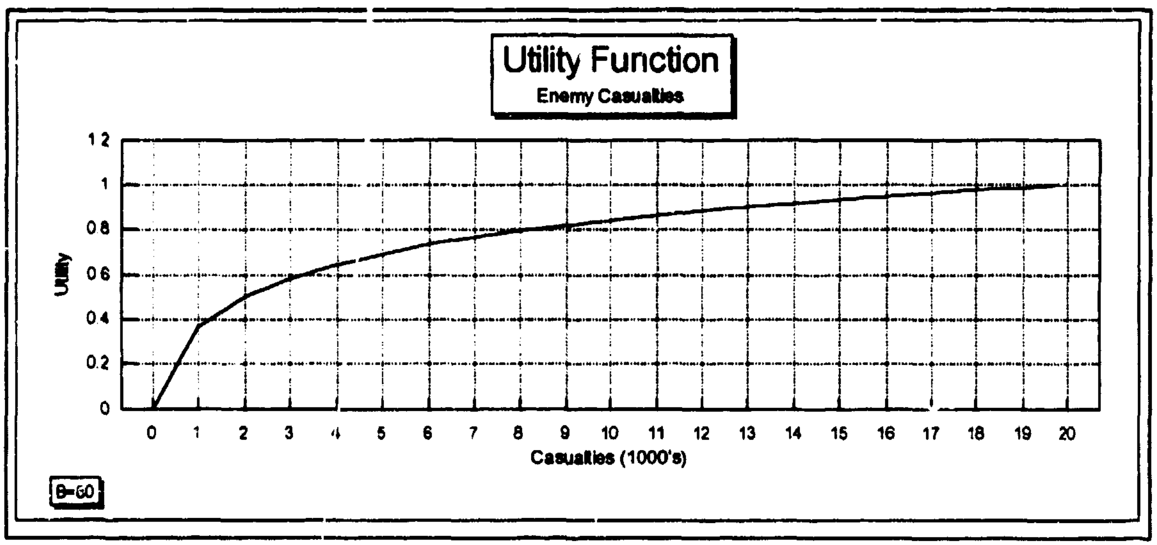

Figure C.2. Enemy Casualties

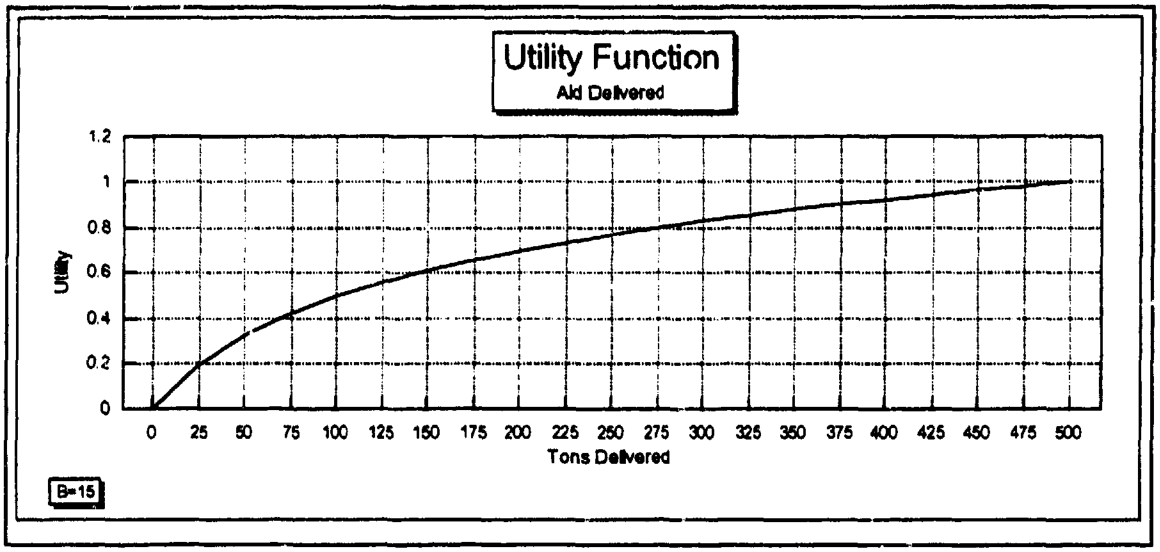

Figure C.3. Aid Delivered

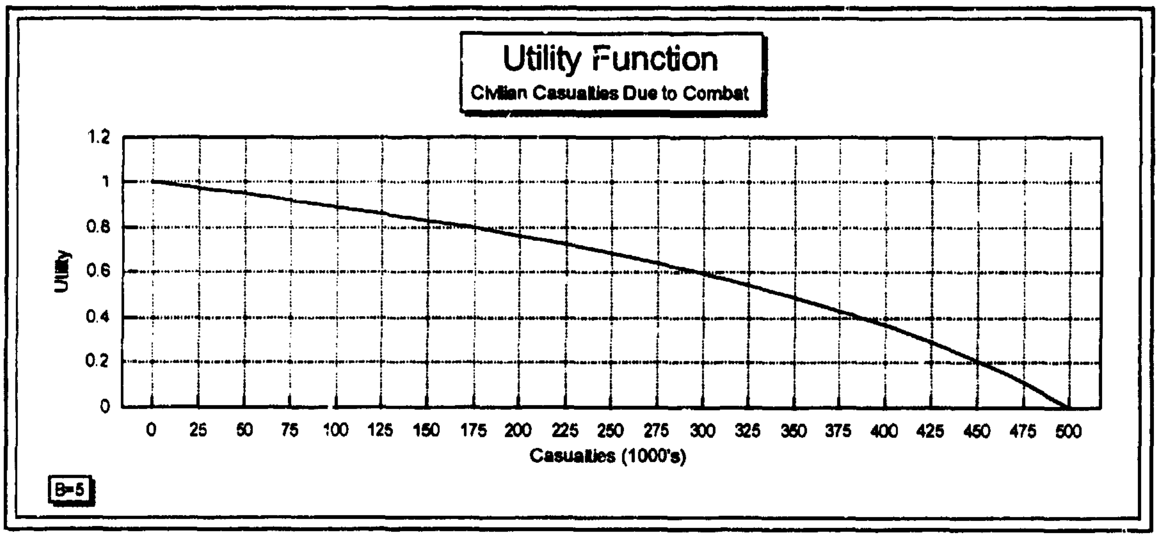

Figure C.4. Civilian Casualties Due To Combat

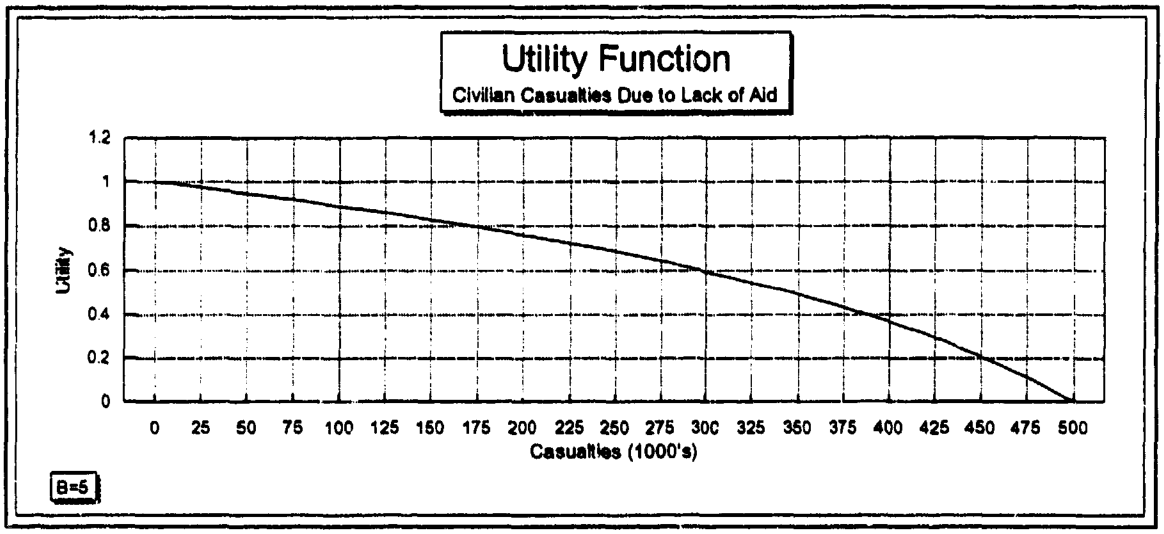

Figure C.5. Civilian Casualties Due To Lack Of Aid

APPENDIX D. SAMPLE MODEL OUTPUT

==================== Initialization Data ====================

Weight for FC 0.4070
Weight for EC 0.4002
Weight for CC 0.0437
Weight for CA 0.0473
Weight for AD 0.1018

Beta (fc,ec,cc,ca,ad)= 2.0 2.0 2.0 2.0 2.0

Blue Forces 1000
Blue Trucks 10
Enemy Forces 5400
Civilians 540000

****

Decision Cycle = 1

****

==================== Node ====================

Node = Seven
DOS = 19.00
Perc DOS = 16.70
COA = Combat
Executed = TRUE
Outcome = Tie
DOS Delivered 0.00
Utility 0.5610
Trucks Used 0
Troops Used 99
Blue Losses 22
Red Losses 22
Civilian Losses 705
Vehicle Losses 0

********** Civilian Forecast **********

2 0
2 1
1 1

--- Marginals ---
Critical 0.2857
Poss Critical 0.4286

Not Critical	0.2857

--- Decision Probs ---

Critical	1.0000
Poss Critical	0.6667
Not Critical	0.5000

********** Threat Forecast **********

1	1
1	2
0	2

--- Marginals ---

Hostile	0.2857
Poss Hostile	0.4286
Not Hostile	0.2857

--- Decision Probs ---

Hostile	0.5000
Poss Hostile	0.3333
Not Hostile	0.0000

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