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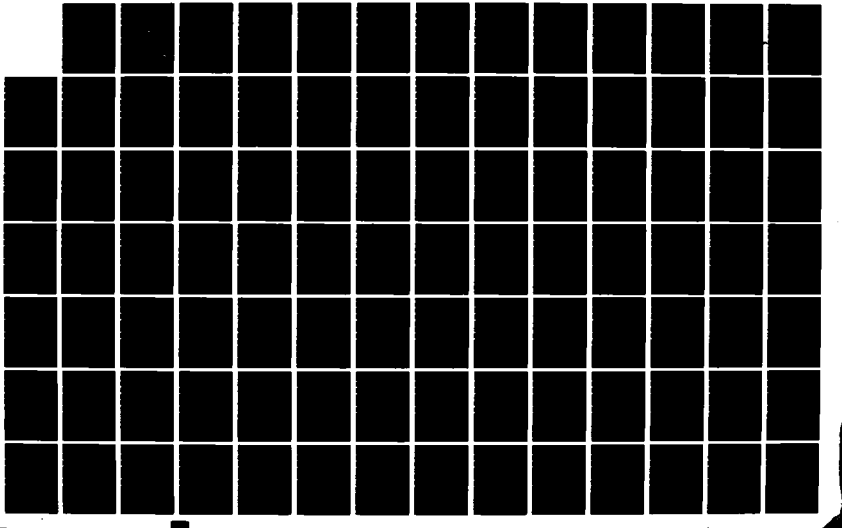

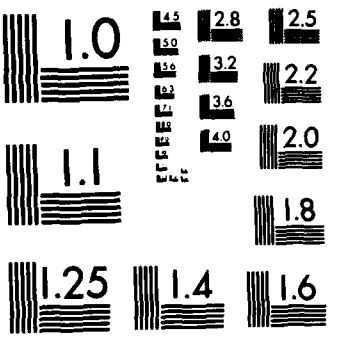

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THESIS

COMBAT ENGINEER
ALLOCATION MODEL

by

Robert V. Kazimer

December 1984

Thesis Advisor: Samuel H. Parry

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE	READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO. AD-A154 172 / 3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Combat Engineer Allocation Model	5. TYPE OF REPORT & PERIOD COVERED Master's Thesis December 1984
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Robert V. Kazimer	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Postgraduate School Monterey, CA 93943	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Postgraduate School Monterey, CA 93943	12. REPORT DATE December, 1984
	13. NUMBER OF PAGES 112
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)	15. SECURITY CLASS. (of this report)
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Airland Research Model, Combat Engineering, Combat Model, Game Theory, Military Engineering, Networks, Obstacles

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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S N 0102-LF-014-6601

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

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Combat Engineer
Allocation Model

by

Robert V. Kazimer
Captain, United States Army
B.S., United States Military Academy, 1978

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN OPERATIONS RESEARCH

from the

NAVAL POSTGRADUATE SCHOOL
December 1984

Author: Robert V. Kazimer
Robert V. Kazimer

Approved by: Samuel H. Parry
Samuel H. Parry, Thesis Advisor

James K. Hartman
James K. Hartman, Second Reader

for Donald R Barr (Acting)
Alan R. Washburn, Chairman,
Department of Operations Research

Kneale T. Marshall
Kneale T. Marshall,
Dean of Information and Policy Sciences

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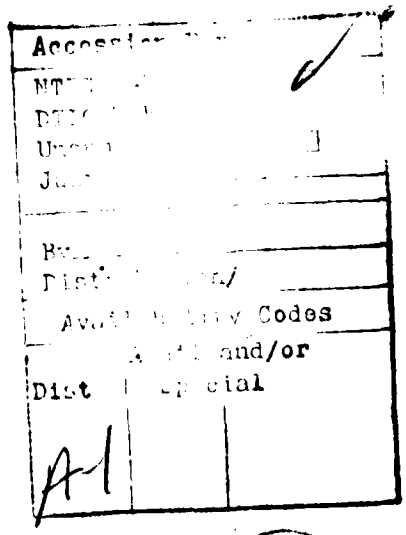
This thesis presents a basic outline and structure for the development of an engineer planning model which will be incorporated into the Airland Research Model at the Naval Postgraduate School. A game theoretic decision structure is proposed within which opposing strategies are evaluated. A generalized resource allocation algorithm is presented to support the countermobility mission of combat engineers within a U. S. Army brigade.



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I. INTRODUCTION

The fundamental mission of the United States Army is to deter war. Deterrence is best served by the maintenance of credible forces guided by sound doctrine. The United States Army has established AirLand Battle doctrine as the body of principles which will guide the operational and tactical employment of its forces should conflict become necessary. The doctrine is predicated upon a nonlinear battlefield where maneuver is as important as firepower, and where unified air and ground operations are conducted deep into enemy rear areas. The focus of AirLand Battle doctrine is warfare within the corps and division, where the operational and tactical levels of war are not clearly separable. [Ref. 1]

The Airland Research Model is a corps level force-on-force combat simulation currently under development at the Naval Postgraduate School [Ref. 2]. The goal of the research is to develop modelling methodologies which are appropriate for the construction of a representation of the AirLand Battle, and in particular the rear area interdiction battle.

The simulation is to be systemic and capable of producing detailed audit trails tracing cause and effect relationships. Rule based "expert systems" are proposed to model command and control decisions. It is envisioned that human players will be used at major decision points to gain further modelling insight. Generalized network methodologies are being developed to represent terrain, transportation systems, communications links, and organizational structures. A generalized value system is being constructed which will permit interdictions to be based on value

comparisons among heterogeneous targets. The concept of time discounting is being considered to impute values to combatants and the units which support them. A variable resolution architecture is proposed which is based on function, situation, and mission. The resolution requirements are being determined by research into the development of planning submodules for each hierarchical level and supporting functional area.

A primary design objective for the Model is the incorporation of prescriptive methodologies where appropriate. The purpose is to provide an analysis tool for investigating "more optimal" methods of planning for and executing the AirLand Battle. Up to the present time, most combat simulations have attempted to describe combat processes, focusing primarily on modelling execution.

The purpose of this thesis is to present prescriptive algorithms which allocate engineer resources to interdict transportation networks in a simulation of the AirLand Battle. A game theoretic structure is proposed in which to evaluate relevant opposing strategies and decide upon courses of action. The structure is applicable to planning at the maneuver brigade level in the Model and constitutes a desirable method for decision making against an active opponent.

Chapter II provides an overview of the combat engineer system as it exists within a U. S. Army corps. The units and missions are outlined to provide a basis for the subsequent discussion of modelling issues. Chapter III discusses modelling resolution issues pertinent to the development of an engineer planning model. It presents a format for a rule based data structure which specifies relationships between resources and their potential effects. Chapter IV discusses the modelling of decisions within the Research Model and establishes the desirability of the game theoretic

construct. Chapter V presents a brigade engineer planning model which employs a two person zero sum game to select both engineer and enemy options for execution. Chapter VI abstracts the resource allocation problem and formulates a mathematical model for the countermobility mission. The focus of the chapter is a heuristic algorithm which specifies resource allocations to establish an expected lower bound on opponent transit times through a transportation network. Chapter VII summarizes the research and provides directions for enhancements and topics for future development.

organic engineer capabilities. These battalions will be placed in a direct support (DS) or general support (GS) command relationship. [Ref. 3: p. 2-8]

The division engineer is the commander of the divisional engineer battalion and is the single engineer point of contact for the division commander. All supporting engineer activity in the division area is coordinated through the organic engineer battalion. Maneuver brigades normally have an engineer company in direct support which performs this coordination function. When engineer assets supporting a brigade exceed the span of control of the company, an engineer task force may be formed. [Ref. 3: p. 2-9]

The brigade engineer is the commander of the company in direct support of a brigade. He allocates engineer platoons and resources to maneuver task forces as the tactical situation demands. Engineers are attached to maneuver units only when time and distance factors prohibit control by the parent organization.

Engineer units not in direct support of brigades are assigned general engineering missions. These missions may be controlled by specific task assignment, or by work coordination lines or areas. Corps units commonly involved in such missions include the engineer combat battalion, the engineer combat battalion, heavy, and the combat equipment support company. [Ref. 3: p. 2-9]

It is evident that resource allocation decisions and planning coordination are the responsibility of the senior engineer at each hierarchical level. While the pool of assets available to support operational missions may vary, this principle governing utilization is well established. Much of the detailed planning which accompanies engineer support operations is decentralized, but subject to review and revision by higher authority. Thus, combat engineers are structured to support the local goals of supported units, subject to constraints imposed by parent organizations.

b. Combat Support Equipment Company

The mission of this unit is to augment engineer combat operations with manned construction equipment. The company functions as an asset pool from which corps and divisional units may be supported. The company can support from one to three engineer combat battalions engaged in general engineering. The company is organized into a headquarters, a dump truck platoon, three equipment platoons, and equipment support platoon, and a maintenance platoon. The company possesses numerous items of equipment including 26 20-ton dump trucks, four 20-ton cranes, nine road graders, nine 18-cubic yard earth scrapers, four scooploaders, and four dozers. [Ref. 3: p. B-19]

c. Engineer Cartographic Company

The corps is supported by one cartographic company which compiles, revises, reproduces, and distributes maps. The corps terrain team is placed in direct support of numbered corps. The team consists of a headquarters, a collection section, an interpretation and analysis section, and an information section. The collection section verifies reports and compiles data needed by the command. The interpretation and analysis section makes studies and predictions based on photo interpretation. The information section stores data and disseminates overlays or reports as needed. [Ref. 3: p. B-18]

E. ENGINEER EMPLOYMENT

The focus of engineer employment in the corps is the support of committed divisions. Corps engineers will often work as far forward as maneuver brigade rear areas. Normally, two corps combat engineer battalions will be located in a division area to meet requirements beyond

1. Erect bridges of various lengths and load classes, up to one 58.5 meter tracked class 60 bridge.
2. 145-ton capacity per haul on 5-ton dump trucks when bridging is immobilized.

The company organization consists of a headquarters, an equipment and maintenance platoon, and two bridge platoons. Major equipment includes 29 5-ton dump trucks, one Bailey bridge set, two 20-ton cranes, one scooploader, one cable reinforcement set, one bulldozer, and a welding shop. [Ref. 3: p. B-20]

4. Corps Special Support Companies

To support corps requirements beyond the capabilities of the organizations reviewed thus far, three additional units would normally be assigned to the engineer brigade. These are an atomic demolition munitions company, a combat support equipment company, and a cartographic company and terrain team.

a. Atomic Demolition Munitions Company

The ADM company supports denial operations in the corps by using atomic demolitions to destroy major bridges, dams, transshipment facilities, and installations. The unit has the following capabilities:

1. Provide liaison and planning assistance for ADM employment.
2. Provide reconnaissance of ADM targets.
3. Prepare and detonate 24 ADM devices.

The company organization consists of a headquarters, an operation section, and six ADM platoons. Each platoon consists of four firing squads of five men and a platoon headquarters. [Ref. 3: p. B-23]

1. 215 meters of bridge or six rafts.
2. Underwater demolitions.
3. Crossing site selection and preparation.

The company contains a headquarters, an equipment and maintenance platoon, and two float bridge platoons. Major equipment includes 30 ribbon interior bays, 12 ribbon ramp bays, 14 bridge erection boats, 56 5-ton bridge transporter trucks, a 20-ton crane, and two bulldozers. [Ref. 3: p. B-22]

d. Engineer Medium Girder Bridge Company

The medium girder bridge (MGB) company is equipped with a hand erectable, heavy duty alloy bridge and has the mission of providing fixed bridge support to the corps. The MGB is used primarily for rapid tactical bridging in the forward main battle area. The company is responsible for the transportation and assembly of the MGB and has the following capabilities:

1. Four 30.5 meter bridges or two 49.7 meter bridges.
2. Simultaneous erection of two bridges.
3. 150-ton capacity per haul on 5-ton dump trucks when bridging is immobilized.

The company is composed of a company headquarters, an equipment and maintenance platoon, and two bridge platoons. The bridge platoons each have two MGB sets. [Ref. 3:. p. B-23]

e. Engineer Panel Bridge Company

The panel bridge company is equipped with the Bailey panel bridge set and has the mission to transport and advise on its erection. The Bailey bridge is a hand erectable, steel component set which is both time and labor intensive. It is generally used to replace tactical bridging, such as MGB, freeing the latter for use in forward battle areas. The company has the following capabilities:

1. One 212 meter bridge.
2. Two 117 meter bridges.
3. Three 85 meter bridges.
4. Six 40 meter rafts.

The company is organized into a headquarters, an equipment and maintenance platoon, and three bridge platoons. Major items of equipment include 24 MAB interior bays, 12 MAB end bays, a 20-ton crane, a scooploader, and a bulldozer. [Ref. 3: p. B-20]

b. Engineer Float Bridge Company

The float bridge company is outfited with the M4T6 bridge and has the mission of transporting and supervising the erection of tactical stream crossing equipment. It can also provide substantial logistics hauling capability when bridging assets are downloaded. The company can provide:

1. 212 meter of floating bridge or nine M4T6 rafts.
2. 80 meters of light floating bridge or six light rafts.
3. Seventy 15-man pneumatic assault boats.

The company is organized into a headquarters, and equipment and maintenance platoon, five float bridge platoons, and a support platoon. The company contains 39 cargo trucks, 60 5-ton stake trucks, five M4T6 bridge sets, six light tactical raft sets, a bulldozer, and a 20-ton crane. Generally, the manpower to erect the bridging in this company must be provided by other units. [Ref. 3: p. B-22]

c. Engineer Assault Float Bridge Company

This company is equipped with ribbon bridge, which is a modular, floating bridge/raft system made of an aluminum alloy. The company has the mission to transport and assemble the bridging and to provide cargo hauling in emergencies. Capabilities include:

b. Organization

The battalion is organized into an HHC, an engineer equipment and maintenance company, and three engineer companies. The HHC is responsible for the normal administrative functions within the battalion. The major assets of the equipment and maintenance company include four cranes, three scooploaders, two bulldozers, three ditching machines a 75-ton-per-hour rock crushing plant, and two bituminous distributors. [Ref. 3: p. B-17]

The engineer companies are organized into a headquarters, a maintenance section, a support section, a horizontal construction platoon and two general construction platoons. The major items of equipment in this company include a 25-ton crane, three road graders, three bulldozers, a scooploader, four 18-cubic yard earth scrapers and six 20-ton dump trucks. [Ref. 3: p. B-16]

3. Corps Bridge Companies

Corps bridge company allocation is dependent upon the number and type of divisions in the corps and the nature of the terrain in the area of operations. The normal allocation objective is to support the corps with six float bridge companies and four fixed bridge companies. All bridging would be assigned to the engineer brigade and generally would be attached to an engineer group. Five types of bridging company will be considered here. [Ref. 3: p. B-29]

a. Mobile Assault Bridge Company

This company is equipped with the mobile assault bridge, MAB, and has the mission of supporting assault river crossing operations. The company can erect bridges and rafts in several combinations including any one of the following:

4. Construct defensive installations.
5. Engage in river crossings.
6. Support the assault of fortified positions.
7. Plan and prepare sites for atomic demolition munition (ADM) teams. [Ref. 3: p. B-15]

b. Organization

The battalion consists of an HHC and four line companies. The composition of the battalion is very similar to the divisional engineer battalion. The major exception is the absence of a bridge company. Other differences include the presence of a construction section of carpenters and plumbers in the HHC, and the use of 5-ton dump trucks for squad vehicles in the line companies. [Ref. 3: p. B-16]

2. Engineer Combat Battalion, Heavy

a. Mission

This battalion is normally allocated to the engineer brigade on the basis of one to four per engineer group. The mission of the battalion is to construct and rehabilitate roads, airfields, pipeline systems, and facilities. Additionally, it increases the effectiveness of divisions, corps, and army groups by providing combat engineer support and general engineer work. It may perform combat infantry missions as required. The battalion is designed to have the following capabilities: [Ref. 3: p. B-16]

1. Provide construction and rehabilitation of routes of communication, bridges, forward airfields, and heliports.
2. Provide general construction of buildings, structures, and facilities.
3. Provide limited reconstruction of railroads and ports.
4. Assist in the emplacement and removal of obstacles.
5. Provide technical assistance in the fortification of positions.
6. Assist in the assault of fortified positions.

D. CORPS ENGINEER BRIGADE

Above division level, engineer forces are tailored to meet the specific requirements of the supported corps or theater. This flexible structure aggregates all attached engineer battalions and companies supporting a corps into an engineer brigade. The brigade is capable of controlling five to seven battalion equivalents through a brigade headquarters and headquarters company. As additional engineer units are assigned to the corps, engineer groups are formed within the brigade. A group has an organic HHC, and may control from two to five battalion equivalents. The brigade may expand to contain from two to four engineer groups. The formation of brigades and groups are based on long term operations. Short term requirements are met by placing the necessary engineer unit in an attached or operational control status. [Ref. 3: p. N-2]

The following sections outline the engineer units which would typically be found within an engineer brigade or group.

1. Engineer Combat Battalion Corps

a. Mission

The engineer combat battalion is normally allocated to the corps on the basis of three per division. Its mission is to increase the combat effectiveness of the corps by means of combat engineer support and general engineer work. It may be tasked to reinforce divisional engineer units and to perform infantry combat missions. The battalion has the following capabilities:

1. Construct, repair, and maintain roads, fords, landing strips, command posts, logistics facilities, and related structures.
2. Prepare and remove obstacles and minefields.
3. Provide water purification.

tools, and obstacle materials to construction sites. The squads are equipped to accomplish demolition, carpentry, and pioneer construction tasks. [Ref. 3: p. B-7]

c. Bridge Company

The type of bridge company found within the battalion will vary with the needs of the division and its geographical location. The company is organized into two heavy raft sections, an armored vehicle launched bridge (AVLB) section, and a company headquarters. The heavy raft sections may have either the mobile assault bridge (MAB) or the M4T6 float bridge. The unit is designed to support brigade sized stream crossings and needs the support of corps bridging assets to conduct divisional crossings. [Ref. &5100.: p. B-7]

The MAB is a self-propelled, amphibious unit which can be driven into the water and linked to form rafts or bridges. When outfited with MAB assets, each section is capable of constructing two 40 meter rafts or one 85 meter bridge. The M4T6 is a hand erectable, air transportable bridge system consisting of pneumatic floats and an aluminum deck of interlocking pieces. With M4T6, each section can construct two 16 meter rafts or two 43 meter bridges. [Ref. 4: p. C-23]

The AVLB section has four launchers and six bridges. The AVLB is mounted on a tank chassis and is employed in the hasty crossing of gaps less than 57 feet wide. The bridge can be launched without exposing the crew to small arms fire, and can be retrieved from either end. [Ref. 4: p. C-20]

In addition to the above bridging assets, the company has a bulldozer for the preparation of crossing site approaches, a crane for material handling, and 15-man pneumatic assault boats. When the unit is equipped with M4T6, it also has two light tactical raft sets. [Ref. 3: p. B-7]

1. Emplace and remove obstacles.
2. Conduct hasty stream crossings.
3. Construct, repair and maintain roads, bridges, and aviation facilities.
4. Support the assault of fortified positions.
5. Provide water supply facilities.
6. Conduct engineer reconnaissance.
7. Provide technical assistance in the use of camouflage and the fortification of positions. [Ref. 3 p. B-6]

2. Organization

The divisional engineer battalion is composed of a headquarters and headquarters company (HHC), four line companies, and a bridge company.

a. HHC

The HHC is organized into supporting staff sections and a heavy equipment platoon. The HHC is responsible for routine administration among companies and has a limited medical and equipment maintenance capability. Logistics are provided to the companies through the HHC. The equipment platoon has four road graders, three bulldozers and two 20-ton cranes which may be formed into teams to support the line companies as necessary. [Ref. 3: p. B-6]

b. Line Company

The line companies each consist of a headquarters platoon and three line platoons. The headquarters platoon is responsible for administration within the company. It also contains two combat engineer vehicles (CEV) a backhoe, a bulldozer, and two scooploaders, which support platoons at the commander's discretion.

The three line platoons consist of a headquarters section and three line squads. The squad vehicle is the M113 armored personnel carrier which transports the squad,

positions to deceive the enemy. Forward engineer elements will construct hasty hull defilade positions for direct fire systems while corps engineers will construct artillery and air defense positions in rear areas. The protection of command and control centers and key logistical facilities will also be a priority for nondivisional engineer units. [Ref. 5: p. 1-5]

4. General Engineering

General engineering refers to tasks performed in rear areas throughout the corps which do not directly contribute to the committed maneuver units. Corps engineer assets are the principal means by which such missions are accomplished. Typical tasks include:

1. Improvement and maintenance of main supply routes.
2. Rear area survivability construction for indirect fire and logistics units.
3. Repair and construction of airfields.
4. Replacement of assault bridging with tactical bridging.
5. Purification of water.

The emphasis on rapid support of forward divisional elements by combat service support units requires the continued development of the corps infrastucture during a campaign. General engineering work contributes toward this purpose. [Ref. 3: p. 2-7]

C. DIVISIONAL ENGINEER BATTALION

1. Mission

Each armored and mechanized division has an organic combat engineer battalion. The mission of this battalion is to increase the combat effectiveness of the supported division by performing tasks in the general engineer mission areas. The battalion has the following capabilities:

engineer forces counter threat mobility. The use of obstacles not only causes delays, but also improves the acquisition and hit probabilities of defending weapon systems. Obstacles are sited to enhance the effectiveness of direct fire weapons and are thus viewed as "combat multipliers". In the formulation of a countermobility plan, care is taken to ensure that obstacle placement does not impede the subsequent maneuver of friendly forces. Conventional obstacles which are frequently used in the division area include:

1. Road craters
2. Destroyed bridges
3. Abatis
4. Minefields
5. Antitank ditches
6. Wire entanglements

Conventional obstacles are often labor and resource intensive and thus must be prepared prior to a battle. To reduce their impact on friendly mobility, obstacles may be prepared but not executed until contact with the threat is imminent. The advent of artillery and aircraft delivered minefields has introduced a dynamic element into countermobility planning. The employment of scatterable mines permits a maneuver commander to create an obstacle nearly anywhere on the battlefield. [Ref. 3: p. 2-3, 17: p. 1-33]

3. Survivability

The increased lethality and range of weapons on the AirLand battlefield requires that significant consideration be given to those tasks which enhance system survivability. The threat has the ability to employ conventional, chemical, and nuclear weapons and to use sophisticated surveillance and target acquition systems. Survivability tasks involve the construction of protective structures, the use of camouflage to conceal locations and the fabrication of false

In addition, engineers have a topographic mission to provide detailed terrain studies and produce maps for the corps. Finally, engineers may be tasked to reorganize and fight as infantry. The nature of requirements in the four main mission mission areas will be considered further.

1. Mobility

An important aspect of the AirLand Battle doctrine is the ability of forces to maneuver effectively across the breadth and depth of an extended battlefield. Mobility relates to those engineer tasks which enable a force to move without restrictive delays due to terrain or obstacles. Mobility tasks may be categorized into five areas:

1. Detection, bypass, marking, and breaching of minefields.
2. Detection, bypass, marking, and reduction, of obstacles.
3. Gap crossing.
4. Construction and maintenance of combat roads and trails.
5. Expedient construction necessary to support army and air force aviation.

While all army units have an inherent ability to overcome many terrain impediments, engineer units are designed to perform those tasks exceeding supported unit capabilities. [Ref. 4: p. iv]

2. Countermobility

The ability to concentrate forces at the decisive time and place is the key to success on the modern battlefield. Thus, the ability to inhibit the maneuver of threat forces is an essential element of AirLand Battle doctrine. Countermobility tasks are those activities which reinforce terrain to delay, disrupt, and attrite the enemy. The construction of obstacles occurs both in offensive and defensive operations and is the primary means by which

II. U.S. COMBAT ENGINEERS

A. GENERAL

> Today more than ever before, the engineer plays a critical role as a member of the combined arms team. As movement and lethality on the battlefield increase, the requirement to reinforce the terrain increases. The engineer brings to the combined arms team a terrain oriented system that enhances the capability of our weapons systems while decreasing the effectiveness of the enemy weapons. [Ref. 3: p. iii]

The purpose of this chapter is provide an overview of the combat engineer system as it exists within a U.S. Army corps. This system is comprised of a variety of units, from organic divisional engineer battalions to special purpose organizations responsible for atomic demolitions. Since the focus of study in the Airland Research Model effort is armored and mechanized combat, the discussion in this chapter will be confined to those engineer units which support such forces. First, the general mission areas for which engineers have responsibility will be presented. The structure of divisional and corps engineer units will then be outlined. Finally, principles for engineer employment within the corps will be discussed.

B. MISSION AREAS

The Army AirLand Battle doctrine specifies that engineers provide support to maneuver forces in four main mission areas:

1. Mobility
2. Countermobility
3. Survivability
4. General engineering

The presentation of a framework for representing the planning of combat engineer resource allocations is the subject of the present study. This chapter briefly outlined the missions, capabilities, and structure of engineer units within a corps. It provides a foundation for the following chapters which discuss issues relevant to modelling the engineer system.

III. MODELLING THE ENGINEER SYSTEM

A. GENERAL

The purpose of this chapter is to establish a framework for representing planning in the combat engineer system. The issues of modelling resolution and mission representation are discussed in sufficient detail to permit the later development of prescriptive planning methodologies which specify the allocation of engineer systems and resources. Emphasis is on the resolution necessary for planning purposes alone and should be clearly differentiated from the details of execution modelling which are to be addressed in future research.

The first sections of this chapter focus on the resolution issues necessary to develop decision criteria for engineer planning. The chapter concludes with a discussion of the rule based decision table which will guide resource allocation.

B. ENTITY REPRESENTATION

This section presents a general discussion of the issue of modelling resolution. Modelling implies abstraction and in most instances requires the selection of a small number of variables thought to be most significant in the system under study. It is necessary for the modeller to identify and categorize the relevant variables before a final selection is made. This permits an appreciation for the limitations of the simulation and provides an agenda for future enhancements to the model.

1. Definitions

Entities are objects which will be explicitly represented in the model and include both engineer systems such as units and equipment, and engineer material such as demolitions. Attributes are characteristics which describe the entities and may be divided into two categories: inherent and system state attributes. Inherent attributes will remain constant for an entity under a given set of conditions. Examples of relevant inherent attributes for system entities include:

1. Unit identification
2. Mobility data
3. Task performance data
4. Maintenance data
5. Communications data
6. Surveillance signature

System state attributes will be variable and include:

1. Location in the x-y plane
2. Operational status

Operational status may be categorized into two classes, operative and inoperative. Operative systems are further identified as either currently idle and awaiting assignment to a task or committed to a task at a designated location. Inoperative systems are classified in a manner to be prescribed by research into the modelling of logistics and maintenance [Ref. 11]. The identifiers will discriminate battle damage from routine mechanical failure and will facilitate the maintenance recovery decision logic. Analogous classifications will exist for human systems such as squads and platoons where the decision process relates to medical evacuation and personnel replacement.

Engineer material entities are identified by the following inherent attributes:

1. Standard package name
2. Weight and volume
3. Logistical class

The state attributes include:

1. Location in the x-y plane
2. Quantity in standard packages

The concept of a standard package of obstacle material was developed in previous research and is a modelling convention in which the materials necessary to create one obstacle of a given type are treated as a single entity within the model [Ref. 12: p. 26]. The concept reduces the computational requirements for the transportation and logistics functional areas as well as for the engineer planning model.

2. Effects Modelling

In a general sense there are two methods of representing the contribution of the combat engineer system within the Research Model. The first approach involves explicitly modelling only the effects of the engineer system on the environment. This would involve the modification of terrain attributes to reflect the presence of obstacles, combat trails, fortifications and other combat engineer products without representing the engineer system entities responsible for their creation. Maneuver entities would be confronted with tactical situations requiring supporting decision logic capable of directing actions at obstacles and adjusting for the resulting differences in weapons exchange ratios. The scope of terrain modification could be kept within realistic bounds by applying time and resource constraints to the construction effort.

3. Explicit Modelling

The first approach is a useful abstraction in combat models which focus primarily on direct fire engagements. However, a simulation representing a highly integrated battlefield has different requirements. The explicit representation of selected engineer system entities is necessary to perform sensitivity analyses on the value of various support combinations. For example, the decision to employ an engineer system such as a bridging unit should not only be driven by the need of a maneuver unit to conduct a river crossing, but also by the probability that the bridging will be acquired by enemy reconnaissance and targeted. Additionally, the presence of a bridging entity in the vicinity of a maneuver unit would be a key input for an enemy intelligence module to compute intention.

Engineer equipment is often considered a low density item by logistical support units since it appears in much smaller quantities than combatants such as tanks or armored personnel carriers. This uniqueness poses special difficulties for maintenance units responsible for the repair of engineer systems. The explicit representation of such systems would enable an analysis of the impact of doctrinal employment decisions upon both supported maneuver units and supporting maintenance facilities. In choosing which systems to represent, the modeller must hypothesize the nature and extent of the interconnectivities likely to have the greatest effect upon the variables of concern.

C. ENGINEER MISSION AREA REPRESENTATION

This section relates the traditional engineer mission areas to their implications in the Airland Research Model. Following a review of these mission areas, the focus of effort in the present iteration of model development is identified, and mission tasks are proposed.

1. Mission Areas

As described in Chapter II, the corps and divisional engineer units in the division area of operations are oriented toward accomplishing tasks in four mission areas. Mobility tasks are oriented "on reducing or negating the effects of obstacles to improve movement of maneuver/weapon systems and critical supplies" [Ref. 3: p. iii]. Countermobility tasks involve the reinforcement of existing terrain by the construction of obstacles to delay, disrupt, and attrite the enemy. Survivability tasks involve the development of protective positions and countersurveillance measures which reduce the effectiveness of enemy weapon systems. General engineering relates to actions which maintain, repair, and develop the infrastructure of the corps area. In addition to these four principal mission areas, engineers have a topographic mission to provide terrain studies and map production facilities within the corps. Finally, engineers may be called upon to reorganize and fight as infantry.

The focus of research in the present modelling effort is to identify the structure of a planning methodology which prescribes the assignment of engineer resources to mission area tasks in an efficient manner for a fixed time horizon. Issues to be addressed include the concepts of feasibility and optimality. Defining the set of feasible alternatives, while not a trivial task, can be significantly simpler than demonstrating optimality. Key to the discussion of either issue is the selection of criteria by which each may be evaluated.

It is hypothesized that relevant measures of effectiveness by which combat actions may be judged are functions of time and attrition. The activities of combat engineers have measureable effects upon both the duration and

lethality of engagements. The construction of major impediments to movement may significantly delay the arrival of an attacking force, affording the defender time to reinforce battle positions. Lesser obstacles cause temporary delays which can improve the firing effectiveness of defending weapons systems. Mobility efforts are aimed at overcoming these delays. Survivability tasks, such as the construction of defilade fighting positions, reduce the expected attrition to protected systems. Finally, general engineering tasks, such as the maintenance of supply routes, aid in the logistical support of combat forces.

It is evident that there are complex interactions between engineer tasks and their effects upon time and attrition. This observation might suggest the use of multiple criteria decision making to resolve the engineer resource allocation problem. This field has received considerable attention in recent years and has proliferated a wide variety of approaches toward reconciling differences in desirability of feasible alternatives. However, a strong case can be made to support the use of single objective optimization techniques, as argued by Rosenthal [Ref. 13: p. 28].

In this preliminary stage of model development, time will be the principal criterion by which the feasibility and preferability of alternative plans of engineer resource allocation will be evaluated. Subsequent research on a generalized value system may develop a utility function which encompasses the criteria of time and attrition by abstracting the concept of time to reflect the "tactical difficulty" of a variant [Ref. 14].

Having selected time as the relevant decision variable, only those engineer tasks which have a direct impact on the duration of activities on the model's transportation network will be represented. Thus, preliminary research

emphasis will be placed on mobility and countermobility tasks, with the latter case being the subject of the present study. The survivability and general engineering mission areas will be the subject of future research. Survivability can be implicitly represented during defensive operations by decrementing construction assets to reflect the fortification of battalion task force battle positions. A corresponding adjustment of attrition coefficients in the formulation of Lanchester differential equations will then be appropriate. Similarly, a prescribed quantity of engineer effort can be assessed to maintain supply routes and airfields in operational condition. Topographic missions and the reorganization of engineers as infantry will not be addressed.

The engineer planning model and the obstacle allocation model developed in subsequent chapters specifically address the brigade countermobility mission. While the models do not treat mobility missions, it is anticipated that the general structure proposed will be readily adaptable to such applications.

2. Tasks

The planning of engineer tasks within the Research Model should consider the following tasks, the first three of which are addressed by the present study.

1. Road blockage
2. Cross country route blockage
3. Bridge destruction
4. Obstacle reduction
5. Gap crossing
6. Minefield breaching

Frequently there are several combinations of engineer systems and materials which can accomplish a task. For example, a cross country route may be blocked by assigning

engineer squads to construct a minefield of sufficient size or by tasking a team of bulldozers to construct an antitank ditch. Additionally, a task may involve the accomplishment of a set of activities. Thus another feasible method of blocking a cross country route might involve the emplacement of both a minefield and an antitank ditch. Each method would in general consume different resources and impose dissimilar time delays. Using taxonomy proposed in modelling efforts at the Combat Engineer Research Laboratory(CERL), each unique method of completing a task is called a technique. Techniques may involve a single job or multiple jobs and can be defined in a rule based standard operating procedure (SOP) table. [Ref. 15: p. 10]

D. RESOLUTION OF ENTITIES

This section specifies a selection of engineer entities chosen for representation in the planning model. The entities are those necessary to achieve a rudimentary depiction of the effect of the engineer system on battlefield mobility. First, the nature and material requirements of obstacles on the transportation network will be discussed. This will serve to motivate the subsequent enumeration of units and equipment necessary to emplace and surmount these obstacles.

The Airland Research Model will use the transportation network as a generalized representation of terrain. The network will be comprised of nodes and arcs which will have attributes to describe ground mobility features such as highways, bridges, fields, and rivers. The primary effect of the engineer model on the simulation will be the modification of these network attributes. The development of a network structure is the subject of concurrent research [Ref. 16]. A node represents a point in the x-y plane and

thus has geometric location. Typically nodes will represent such things as road junctions. Arcs connect nodes and thus are line segments in the x-y plane. Arcs may possess a variety of attributes which include such factors as length, width and type. The following discussion establishes requirements which the transportation network must satisfy to support engineer planning.

1. Obstacles

An obstacle may be defined as any obstuction which stops, delays or restricts movement. Obstacles may be categorized as either existing or reinforcing. Existing obstacles consist of naturally occurring features such as rivers and ravines, and cultural features such as villages and canals. Reinforcing obstacles are obstructions created through military effort which capitalize on existing impediments. [Ref. 17: p. 2-2]

While obstacles may be employed in any military operation, they are used most extensively in defensive scenarios. Countermobility doctrine emphasizes three main purposes for the use of reinforcing obstcles:

1. Enhance antitank weapon effectiveness.
2. Delay, disrupt, and attrite the enemy.
3. Enable economy of force actions.

The siting of obstacles is generally based on the location of direct fire antitank weapons and is intended to hold targets at maximum engagable ranges or divert them into areas more favorable to the defender. Principal emphasis is on obstacles which counter tank mobility. In this regard, the minefield is often favored since it can cause tank casualties independent of direct fire weapons. While the variety of obstructions which can be employed is virtually limitless, four types of obstacle will be used in the model:

1. The destroyed bridge.
2. The road crater.
3. The minefield.
4. The antitank ditch.

These obstacles will provide a cross section of the tactical maneuver and combat engineering situations existent on the AirLand battlefield.

a. Bridge Destruction

The destruction of a bridge can be a major impediment to mobility. The transportation network should reflect two bridging situations; the spanning of wet gaps such as rivers and streams, and of dry gaps such as highway underpasses and valleys. Three classes of bridge can be considered by the model:

1. The four lane autobahn bridge.
2. The primary road bridge.
3. The secondary road bridge.

The mix of bridge situation and classification can present unique mobility and countermobility requirements for the engineer model.

The destruction of a bridge need not be complete to serve a useful military purpose. Frequently it is necessary to destroy only one span of a large bridge to force the enemy onto an alternate route or to prompt the commitment of his bridging assets. The representation of bridge destruction in the model will involve the allocation of a specified number of bridge demolition packages and combat engineer squads to the target bridge. A standard package will consist of the explosives and expendable items necessary to destroy a secondary road bridge. Other bridges will require a multiple of such packages.

During mobility operations the engineer model can plan for overcoming a destroyed bridge by one of the following methods:

1. Select an alternate route.
2. Conduct a hasty river crossing.
3. Erect a fixed span tactical bridge.
4. Construct an immediate bypass.

Some or all of the above methods may be infeasible within the given situation and available engineer assets.

River crossings are complex operations which involve the construction of combat trails to and from crossing sites, the assembly of rafts and float bridges, and the coordination of maneuver units and fire support. Such crossings are both time and resource intensive and greatly increase the vulnerability of crossing forces.

The erection of fixed bridging may be possible if the gap is sufficiently short. The AVLB is generally preferred if the gap is less than 57 feet. Other gaps would require the use of MGB or Bailey bridge and the allocation of engineer manpower.

The constuction of a bypass may be allowed by the terrain in the case of a dry gap. The model would allocate earthmoving assets such as bulldozers and scooploaders to effect a modification of trafficability parameters.

b. Road Crater

A road crater involves the explosive excavation of a road surface and substructure. When properly placed and reinforced with mines, it is an effective obstacle against wheeled and tracked vehicles. Two methods of creating road craters will be considered by the model:

1. The hasty road crater.
2. The M180 cratering kit.

The hasty road crater is emplaced by making boreholes across the road at specified intervals, loading them with explosives, and detonating them simultaneously. The resulting crater is 20 to 25 feet across and 6 to 7 feet

deep. The width is determined by the dimension of the road to be obstructed. The explosives necessary for a hasty crater on a secondary road will form a standard package. A primary road or an autobahn will require several packages.

The M180 cratering kit is a self-contained system which consists of a shaped charge for hole boring, and a rocket propelled cratering charge mounted on a tripod. Three to five kits are generally required to create a crater with characteristics similar to those of the hasty method. The M180 kit is frequently preferred over the hasty method because it requires less time to prepare. An M180 standard package will represent the number of kits required in cratering a secondary road.

The engineer model can overcome the effects of a road crater by one of the following means:

1. Select an alternate route.
2. Bridge the crater.
3. Fill the crater.
4. Create a bypass.

The AVLB will be the primary means of bridging a crater. It will also be possible to use MGB to span the gap, although such use is generally not time efficient. The filling of a crater will involve the allocation of earth-moving equipment such as the CEV, bulldozer, and scooploader. The creation of a bypass will be situation dependent and, in many cases, may not be possible. If the crater is flanked by a minefield, breaching equipment would be necessary.

c. Minefield

Mine warfare doctrine is evolving from the concept of large linear minefields to the use of small mined areas scattered across the battlefield. Both mine munitions and the means of their delivery vary greatly. Conventional

mines are explosive devices which may be mechanically or hand emplaced in fixed or random patterns. Scatterable mines are designed to self-destruct after a specified period of inactivity and may be emplaced by ground dispensers, artillery, or aircraft. Minefields created by either conventional or scatterable means can be effective obstacles against both personnel and armored vehicles. [Ref. 17: p. 5-2]

Minefields are categorized according to their purpose and vary from those protecting fixed installations to "phony" minefields designed to deceive the enemy. The engineer model will employ two types of minefield:

1. Point minefields.
2. Tactical minefields.

The means of emplacement will be limited to conventional and scatterable mines delivered by ground systems.

Point minefields are used to rapidly delay and disrupt an enemy and to compliment the effect of other obstacles. Brigade commanders are authorized to employ point minefields and this authority may be delegated to the battalion level [Ref. 3: p. 5-15]. The model will represent two methods of making a point minefield. The first method will be the hand emplacement of conventional mines by an engineer squad. The munitions necessary to mine a secondary road or another obstacle will form a point standard package. The second method will involve the use of MOPMS; a scatterable system which dispenses 21 antitank or antipersonnel mines in a 35 meter radius semicircle. A MOPMS standard package will consist of the kits necessary to create an effect roughly equivalent to that of a point standard package.

Tactical minefields are generally more extensive than point minefields and hence require more time and material assets to emplace. They may be used to stop or

b. Two Person Zero Sum(TPZS) Game

This game is characterized by two players whose interests are in complete opposition. That is, what one player wins, the other losses. Such conflicts are also called matrix games. The TPZS game is the mathematically most well developed of a wide spectrum of conflict situations in that it is possible to unambiguously describe a game solution.

c. Strategy.

A pure strategy is a predetermined plan that prescribes for a player the sequence of moves and countermoves made during a complete game. Thus, it is a complete rule for decision making.

d. Payoff

A payoff is the numerical value received or lost corresponding to each alternative of the other player in a TPZS game. ·All payoffs are tabulated in a matrix where the rows and columns represent the strategy choices of the two players. By convention, payoffs are made to the row player who attempts to maximize his minimum level of gain. Conversely, the column player seeks to minimize his maximum loss.

e. Complete Information

A basic assumption of any game is that all players are aware of the extensive form of the game, that is, they are aware of all the legal moves at each stage of the game and of the probability distributions involved. Additionally, they understand the utility which the outcomes represent for themselves and for their opponent. [Ref. 9 p. xi]

approach is that complex decisions are often hard to automate, even when the goal is not optimality. There are disadvantages to this method. The training of gamers may be quite time consuming and many may be required to get results that depend on the issues under study and not game playing skills. Secondly, the long playing times of such games often insures that only a few variants will be examined. [Ref. 6: p. 249]

Two observations appear relevant. If it is determined that the answers to issues are likely to be the same over a wide range of situations, monotonic rules are desirable since they permit a more detailed model to be used. However, if the decisions made are likely to produce different results, the game theoretic approach is preferable. Due to the difficulty of projecting the effect of decisions against an active opponent in AirLand warfare, the use of game theory will be pursued further.

D. GAME THEORY OVERVIEW

The theory of games can provide an optimal method for making planning decisions, given the situation can be formulated into a game theoretic context. In general, one wishes to know which of several available employment options should be exercised in view of an opponent's capabilities. This section will introduce the concepts necessary to discuss the application of game theory to decision making in the allocation of engineer resources.

1. Definitions

a. Game

A game may be described as a conflict situation among N players conducted under a prescribed set of rules with known rewards. The rules define the elementary activities or moves of the game. [Ref. 7: p. 184]

4. Simple Rules

This method employs decision rules the effect of which varies monotonically with a global MOE. For example, suppose that it is accepted that the slower a force is caused to move, the better the defender's outcome will be. A simple rule could be formulated which prescribes the application of more obstacles along an enemy avenue of advance. A problem is that while such a rule might appear to be monotonic, it may not. In the above example one could argue that creating extensive delays along one route might divert the enemy to an adjacent, less capable defender resulting in a defeat. The difficulty with simple rules is that demonstrating them to be monotonic may be as difficult as proving optimality. Monotonic behavior occurs if all decisions are game-theoretic optimal. However, this fact is of little practical value in determining decision rules. The advantage of this method is that simple rules are easy to understand and explain. However the effect of the rule in the simulation may not be readily evident. [Ref. 6: p.248]

5. Modelling Human Decisions

This method describes attempts to categorize the reponse of some desirable class of human decision makers over a wide range of situations. Statistical techniques may be used to define median responses to a tactical problem. The method does not in general provide optimal decisions, but may yield consistently reasonable ones. At the current time this method has found little application in large scale combat simulations. [Ref. 6: p. 249]

6. Human Interaction

This method uses human gamers to interact with the simulation and make decisions. The advantage of this

gives the best indication of what each side in the conflict can do. The disadvantage is that in most situations of interest the number of options far exceeds the ability to enumerate them. Thus the simulation is forced to be relatively simple, and perhaps less believable to a decision-maker. An alternative method is to construct a reduced set of choices for each side in the conflict and determine the game theoretic solution for a more detailed simulation. The problem is that in the reduction of options, one may omit superior choices from consideration. [Ref. 6: p.241]

2. Optimization Algorithm

This method involves the use of a mathematical programming technique such as linear, nonlinear, or dynamic programming, to optimize a local MOE. For example, this method may pursue the goal of maximizing attrition to the enemy as a means toward the end of winning the campaign. This method is usually not optimal in the game theoretic sense. To the extent that the algorithm chosen reflects decisions consistent with military judgement, it may be useful. However, because the method is a sub-optimization, it can result in decisions far from the global optimum. In general one may not know the quality of the choices made. [Ref. 6: p. 243]

3. Expected Opposition

In this method one attempts to gain intelligence as to what the opponent will do and then constructs countering strategies. The method may involve the formulation of fixed rules or of algorithms with parameters chosen to reflect the opponents tactics. While the method attempts to optimize against the perceived intent of the opponent, it does not fully address his capabilities.

superior simulation. The representation of decisions may be of secondary interest to the modeller and thus receive little attention. The difficulty with this situation is that simulations are often used to determine or validate policy. The inability to accurately model employment choices may lead to analyses which misrepresent the capabilities of the hardware and thus result in flawed doctrine.

In the modelling of ground combat there is a wide variety of decisions which must be portrayed at each hierarchical level. These choices may include: what unit to move, where and when to move, what units to hold in reserve, what route to use, and how to employ supporting assets. The answers to these questions are often written into the logic of the model in such a manner that the range of research issues for which the model may be used is unnecessarily limited. It is therefore useful to conduct a brief survey of decision modelling methodologies. The following methods will be considered:

1. Game theoretic with a global objective
2. Optimization algorithm with a local goal
3. Decisions based on expected opposition
4. Decisions based on simple rules
5. Modelling human decision making
6. Decisions by human interaction

1. Game Theoretic

In the game theoretic approach one attempts to make an optimal decision in accordance with a global measure of effectiveness(MOE). The MOE is the overall decision criterion for the conflict, for example the outcome of a battle, and not for a specific engagement in the battle. One selection method involves the use of linear programming to describe an optimal course of action from among all allowable options. The advantage of this method is that it

instuctions designating the type of activity to be conducted, the appropriate times and locations to be considered, and the threshold parameters which constrain the problem. The continuing development of the functional area planning submodules will identify the relevant parameters and the submodules responsible for generating their values. To illustrate the information flow in the Research Model, it is helpful to examine the decision process in a generalized stepwise sequence [Ref. 2].

1. Receive general mission guidance.
2. Formulate courses of action for each functional area.
3. Integrate all courses of action and conduct feasibility checks.
4. Iterate as necessary to insure feasibility.
5. Formulate a detailed operations order.
6. Develop execution instructions for each functional area.
7. Pass control to the execution module.
8. Check decision thresholds for the operations order. If violated return to step 1.
9. Check decision thresholds for aspects of the execution plan. If violated return to step 6.
10. Continue execution.

The present phase of Model development is directed toward establishing the decision structures necessary to accomplish Step 6.

C. DECISION MODELLING

> In virtually all simulations of conflict that are complex enough to be useful, there are decisions that must be modelled. How these decisions are modelled frequently has a major impact on the results of the simulation [Ref. 6: p. 237].

In the construction of models of conflict great pains are often taken to model hardware in explicit detail with the belief that such efforts will naturally result in a

IV. DECISION STRUCTURE

A. GENERAL

The current goal of research in the Airland Model study effort is the development of a planning module which can generate execution strategies. One approach is to employ a game theoretic framework to select from among a finite set of strategy options.

This chapter will discuss the use of a game theoretic approach to decision making in planning. First, the role of planning in the simulation will be discussed. Next, common methods of modelling choice will be enumerated. Finally, a brief introduction to the theory of games will be presented with emphasis on the two person zero sum game.

B. PLANNING MODULE OVERVIEW

In the Airland Research Model the functions of planning and the details of execution are divided into two distinct modules. The planning module includes the decision algorithms and thus must generate courses of action, select the variant to be executed, and transmit the necessary instructions to the execution module. The planning module consists of several submodules which reflect the planning functions of each hierarchical level of the maneuver task force organization. Each combat support and combat service support functional area will also be represented by a planning submodule. [Ref. 2]

The eventual goal for the planning module is to have a structure which can take general guidelines on the nature of a mission and produce a detailed set of operating instructions. At present, the input will be specific mission

TABLE 6

Sample SOP Table

TASK: Block Secondary Road / No Offroad Bypass

TECHNIQUE	SYSTEM	QTY	MATERIAL	QTY	DURATION(hr)	DELAY(hr) I	II	III	IV
Road Crater	sqd	1	M180	1	1	1	.3	.2	.2
Road Crater	sqd	1	Hasty	1	1.5	1	.3	.2	.2
Pt. Minefld	sqd	1	MOPMS	1	.5	1.5	.5	.5	.5
Pt. Minefld	sqd	1	Point	1	1	1	.5	.3	.2
Road Crater and Pt. Minefld	sqd	1	M180 MOPMS	1 1	1.5	2	1	1	.5
Road Crater and Pt. Minefld	sqd	1	Hasty Point	1 1	2.5	2	1	.5	.5

This chapter examined the engineer system and the issues relevant to abstracting it into a conceptual model. The SOP table provides a framework for discussing engineer resource allocation in a more mathematically formal context. The next chapter discusses the modelling of decisions within the Research Model and establishes the desirability of a game theoretic construct.

To show the conceptual format of the table, the case of a two lane secondary road through a narrow defile will be considered. The situation reflected on the transportation network would indicate that off road mobility is not possible. Such constrictions form ideal obstacle sites since less material and effort are required to cause delays. Table 6 illustrates this case with hypothetical data. Future research will be directed toward constructing the data base required by the engineer planning model.

The use of an SOP table can be illustrated by explaining the entries of the first row of Table 6. The first entry specifies the type of obstruction which will be indicated on the transportation network. Here, a standard road crater will be designated. The next two entries specify the type and quantity of engineer systems which must be allocated to accomplish the task by this technique. Here, one combat engineer squad must be dedicated to the job. The following two entries indicate that one M180 engineer material standard package is necessary and will be expended in creating the road crater. As specified next, the construction effort will require the squad to remain on site for one hour.

The final series of entries represent the expected delay in hours which the road crater will impose on any one of several categories of units. These categories can reflect a mix of inherent mobility characteristics and supporting engineer availability. For example, category I could be a wheeled transportation unit, while category II might represent the same unit with engineers in direct support. Analogous categories could be tabled for armored and mechanized forces.

TABLE 3

Corps Engineer Combat Battalion

Entity	Quantity
Combat Engineer Squad(5 ton)	36
Bulldozer	10
Scooploader	10
Road Grader	4

TABLE 4

Engineer Combat Battalion, Heavy

Entity	Quantity
Bulldozer	9
Scooploader	3
Road Grader	9
Scraper(18 cubic yard)	12

TABLE 5

Engineer Medium Girder Bridge Company

Entity	Quantity
Medium Girder Bridge Platoon Two 100ft brg/plt or One 160ft brg/plt	2

E. STANDARD OPERATING PROCEDURE TABLE

An SOP table will specify allowable combinations of engineer system entities and material packages capable of accomplishing a given task. The duration of the engineer activity and a vector defining the expected delay value of the task against various threats also will be contained in the table.

2. Units and Equipment

To support the obstacle construction and destruction tasks which will be modelled on the transportation network, several system entities have been selected for explicit representation. Units will be resolved to the combat engineer squad level since squads are capable of independently accomplishing many mobility and countermobility tasks. Major items of equipment are frequently tasked individually or combined to form teams, thus necessitating their individual resolution.

Table 2 identifies the systems which will be represented in a divisional engineer battalion. Table 3, Table 4, and Table 5 specify the corps level systems which will augment divisional engineer units.

TABLE 2

Divisional Engineer Entities

Entity	Quantity
Combat Engineer Squad(M113)	36
Combat Engineer Vehicle(CEV)	8
Bulldozer	8
Scooploader	8
Road Grader	4
Armored Vehicle Launched Bridge(AVLB)	
Launcher	4
Bridge	6
Mobile Assault Bridge(MAB) Platoon*	2
Two 40m rafts/plt	
or One 85m bridge/plt	
M4T6 Bridge Platoon*	2
Two 16m rafts/plt	
or Two 43m bridge/plt	

(*NOTE: A division will have either MAB or M4T6)

The engineer model will allocate earthmoving equipment such as bulldozers, scrapers, scooploaders and CEVs to represent ditch construction. Normally, equipment teams are formed to accomplish this task. A tank ditch standard package will reflect the diesel fuel necessary for a team of two bulldozers to construct 100 meters of ditch in average soil. Such an excavation will generally require 1.5 hours [Ref. 17: p. 6-39].

While most tracked vehicles can eventually overcome a tank ditch by wearing down its walls, engineer effort can be allocated to speed the task. The engineer model can assign earthmoving equipment or assault bridging such as the AVLB to support ditch breaching.

e. Engineer Standard Packages

Table 1 summarizes the standard packages of expendable obstacle related materials which will be represented.

TABLE 1

Obstacle Standard Packages

Bridge Demolition	
Bridge	package
Road Crater	
M180 crater	package
Hasty crater	package
Minefield	
MOPMS	package
Point	package
M57	package
GEMSS	package
MFJ	package
Minefield Breach	
Bangalore	package
M157	package
M173	package
Antitank Ditch	
Diesel	package

delay enemy attacks, block penetrations, deny withdrawl, and prevent reinforcement. The division commander has the authority to employ tactical minefields and this authority may be delegated to the brigade level. [Ref. 17: p. 5-8] Three means of creating a tactical minefield will be represented in the model; the hand emplaced MFJ standard pattern minefield, the M57 mine dispensing system, and the GEMSS scatterable minefield. In each case a standard package will consist of the mine material necessary to emplace a 100 meter minefield.

The breaching of minefields by the engineer model can be represented by the allocation of three types of demolition kits. Antipersonnel minefields will be breached by bangalore torpedo standard packages. The bangalore torpedo kit consists of tubes of explosives which are connected together and pushed into position by hand. Their detonation clears a path approximately two feet in width. Antitank minefields will be breached by allocation of either an M157 or M173 standard package. The M157 demolition kit is a tank emplaced line charge which clears a path four meters wide and 90 meters long. The M173 kit is a rocket projected line charge which creates a path 4.6 meters wide and 70 meters long. [Ref. 4: p. C-2]

d. Tank Ditch

Tank ditches are linear excavations which slow, disrupt, and confuse the advance of attacking forces. The effectiveness of a ditch depends on its dimensions, the soil characteristics, and the type of vehicle attempting a breach. While the design of tank ditches varies, the engineer model will represent a standard rectangular ditch 3.3 meters across and 1.5 meters in depth. Such a ditch normally imposes a five to ten minute delay on tracked vehicles in the absence of engineer support. [Ref. 17: p. 6-28]

f. Perfect Information

By this concept it is meant that each player knows at all times the precise state of the game including the past history of moves. This is to say that nothing is concealed from the player when a choice is made. Often games present situations where a choice must be made in the absence of such knowledge. These are said to be games of imperfect information. [Ref. 8: p. 19]

g. Normal Form

The normal form of a TPZS game is a formulation where the strategies are enumerated and the payoff matrix is expressed. The two players each choose a pure strategy unaware of the other's choice. [Ref. 8: p. 23]

h. Dominance

A strategy can be eliminated from a player's set of options if there is another strategy in the set which is always at least as good regardless of what the opponent does. The eliminated strategy is said to be dominated and would never be used by a rational player.

i. Saddle Point

If each player has a single best pure strategy, then the intersection represents a saddle point and the payoff is called the value of the game, v^*. The two strategies are said to be optimal pure strategies and would be used by rational players every time since they ensure the payoff v^*, which is the best either player can expect.

j. Mixed Strategy

A TPZS game which does not have a saddle point has no solution in pure strategies. One can generalize the

concept of solution to include a probability distribution on the set of pure strategies for a player. In accordance with the MINIMAX theorem, every finite TPZS game has optimal mixed strategy vectors $\underline{x}^*$ and $\underline{y}^*$ and a game value v^*. Thus, a player makes a choice between pure strategies regulated by chance. This use of randomization in the choice of a course of action results in a lack of absolute predictability on the part of either opponent. This latter point assumes the existance of at least two non-zero elements in both $\underline{x}^*$ and $\underline{y}^*$. [Ref. 8: p. 31]

k. Bimatrix Game

In the TPZS game it was assumed that the two players' goals are in direct conflict. Generally, the interests of the two players may not be exactly opposed. This implies that one player may value the loss of one unit of payoff in a manner different than his opponent. Often cooperation between the players could result in greater returns than if each acted only in their own interest. Cooperation may be prohibited by the rules of the game. Such a situation is called a noncooperative bimatrix game. In general, the solution to such a game is controversial since each player may have his own preferred solution which, if pursued, could be worse for both. [Ref. 8: p. 78]

2. TPZS Solution Method

Linear programming provides a powerful method for determining the solution to a finite TPZS game in normal form. To illustrate the formulation of such a game, consider a conflict in which row player I has m pure strategies and column player II has n such strategies. Since I is the maximizing player, he will attempt to maximize his minimum gain, v, subject to n inequality constraints. These state that the average payoff to I is at

least v when II uses one of his n stategies and I uses mixed strategy $\underline{x}$. Additionally, $\underline{x}$ is constrained to be a proper probability distribution. The solution to this program, v* and $\underline{x}^*$, represents the game value and I's optimal mixed strategy. The dual to this formulation yields II's optimal mixed strategy, $\underline{y}^*$, and the same game value, v*. This latter fact is the essence of the MINIMAX theorem. [Ref. 10: p. 31]

V. BRIGADE ENGINEER PLANNING MODEL

The purpose of this chapter is to present an algorithm which employs a TPZS game formulation as a decision model for selecting a brigade obstacle plan in the Airland Research Model. The algorithm will be referred to as a brigade engineer planning model and in general could be formulated to support either the mobility or the countermobility mission of engineers supporting a brigade. The mobility formulation will be the subject of future research and will not be considered further.

A. BACKGROUND

The brigade provides a convenient point of departure for the discussion of engineer planning. First, the basic level of unit resolution in the Research Model is the battalion task force. Choosing a middle level hierarchical unit such as the brigade permits a general discussion of the linkages between its superior and subordinate units; the division and battalion task force, respectively. Second, it is at the brigade level that detailed obstacle plans are prepared [Ref. 17: p.4-6]. Corps and division obstacle plans are primarily a means for transmitting a "countermobiliy concept" to subordinate units [Ref. 17: p.4-5]. These higher level plans also specify allocations of obstacle materials and additional engineer units which are deemed necessary for the brigade to successfully execute the intentions of the corps and the division.

A brigade conducting a defend or delay mission is normally supported by a divisional combat engineer company which is placed in direct support. This company is usually

augmented by the divisional engineer battalion with additional resources such as engineer platoons, earthmoving equipment, and obstacle material. The brigade engineer must allocate both organic and supplemental assets to the battalion task force sectors within the brigade to best support the countermobility mission of obstructing enemy maneuver. In addition, the brigade engineer issues guidance to his subordinate engineers concerning the type of threat against which the obstacle plan is to be constructed and the time available for its emplacement.

Because planning decisions concerning obstacle preparation must be made hours or days in advance of the battle, the specific enemy configuration which will confront the brigade is often uncertain. However, it is possible for the division to identify for the brigade the type of threat which may maneuver into the brigade sector during the current planning cycle. From this information, it is possible to enumerate a range of tactical options which the enemy could employ in negotiating the brigade sector.

Similarly, the enemy is uncertain as to how the defending brigade will prepare the sector with obstacles. The organization, capabilities, and doctrine of the brigade are known to the enemy, as is the terrain in the sector. The enemy must plan for the deployment of its forces well in advance of encountering the brigade. In general, it is not until the enemy actually arrives at the sector and conducts extensive reconnaissance that the obstacle plan becomes evident.

B. OVERVIEW

In the Airland Research Model it will be necessary to abstract the preceding situation into a mathematical formulation which can specify an allocation of engineer resources

to support the countermobiliy mission. It is proposed that a TPZS game be the decision model from which engineer and enemy employment strategies are selected for implementation. The convention of referring to the defending engineer force as Blue and the attacking enemy force as Red will be adopted for clarity.

The brigade engineer planning model is an algorithm which takes input from the Research Model, formulates and solves the engineer and enemy allocation problems as a game, and selects a course of action for each. The following assumptions are pertinent to the game construct:

1. The possible Red attack options are known to Blue and the Blue obstacle allocation options are known to Red.
2. Both Red and Blue use the same criterion in the calculation of payoff values for the game and their objectives are completely opposed.
3. Both Red and Blue make their allocation decisions at the same time. This assumption can be generalized to state that at the times that decisions are made, neither opponent has any advantage over the other concerning information about the game.

In brief, the game is formulated in the following manner. Each Blue engineer strategy B(i); i= 1 to m, represents a unique allocation of available engineer assets among the battalion task force sectors which results in a brigade obstacle plan. A sector defines a portion of the transportation network and corresponds to the military concept of an avenue of approach. The Blue obstacle plan is not modified in response to Red's allocation decision and thus is a one stage strategy. Each Red enemy strategy R(j); j=1 to n, is a unique assignment of available enemy units to avenues of approach. This assignment is not changed in response to Blue's decision. However, Red is assummed to learn the obstacle plan upon encountering the brigade sector and therefore selects the minimum time path. Thus, Red plays a two stage strategy. Each payoff value a(i,j) is a weighted average of the expected minimum transit times of Red units

through the interdicted sectors to which they are assigned. The obstacle interdictions are specified by an obstacle allocation model discussed in Chapter VI.

It is clear that a more comprehensive brigade game could be formulated with strategies involving many factors other than those specifically concerning engineers. For example, it may be argued that the positioning of battalion task forces within the brigade could be specified by the strategies as could the definition of sector boundaries dividing those units. Ostensibly, any variable defined to be controlled by the brigade could be used in generating strategies. However, for the purposes of the brigade engineer planning model the locations of battalion task forces and their sector boundaries will be derived as input from a detailed operations order.

C. MODEL INPUT

During the execution of operations within the Research Model, events will occur which trigger the issuance of new instructions to subordinate units. The question of how operations orders can be dynamically generated within the Model is a topic of active research. One approach is to employ generic mission "templates" which configure combatants to fit with the terrain and specify unit missions. The Engineer Planning Model will require several items of information once a countermobility mission is specified.

1. Planning Horizon

The time available to perform obstacle construction tasks must be specified in the operations order to the brigade. This time period should reflect an interval from the receipt of the the mission to the anticipated arrival time of an enemy unit at the forward boundary of the brigade

sector. For plannning purposes it is required that all obstacle interdictions to the network be completed within this period. This simplification avoids calculating unique arrival times for the enemy at each potential obstacle site and reduces the computational effort necessary to establish the feasibility of an interdiction.

2. Unit Sectors

The spatial distribution of units on the battlefield must be established as input down to and including battalion task force sectors. As previously mentioned, such sectors sit astride likely enemy avenues of approach and therefore delineate sections of the transportation network of interest for obstacle interdiction. The methodology for subdividing a general network into sub-networks is a key issue in template research. The current approach is based upon identifying natural terrain compartmentalizations which lead to specifying independent transportation networks for each sector.

The use of minimum transit time through a sector as a payoff criterion implies the existence of a unique set of local source and sink nodes at the front and rear of each battalion sector. Otherwise, multiple minimum paths of different values could be said to exist along an avenue of approach. A problem of definition exists in identifying for the model which node to select as a source or sink. In general, the sector network as defined by the templating procedure may not contain obvious candidate nodes for this selection. One possible solution could be to create a notional node to represent a source or sink when no existing node satisfied that purpose. Dummy arcs of zero cost could then connect the notional node to existing nodes at or near the sector boundaries. Figure 5.1 illustrates a typical brigade sector for conducting a delay operation along three

avenues of approach. Each avenue is defended by a battalion task force and is treated as an independent interdiction problem by the obstacle allocation model.

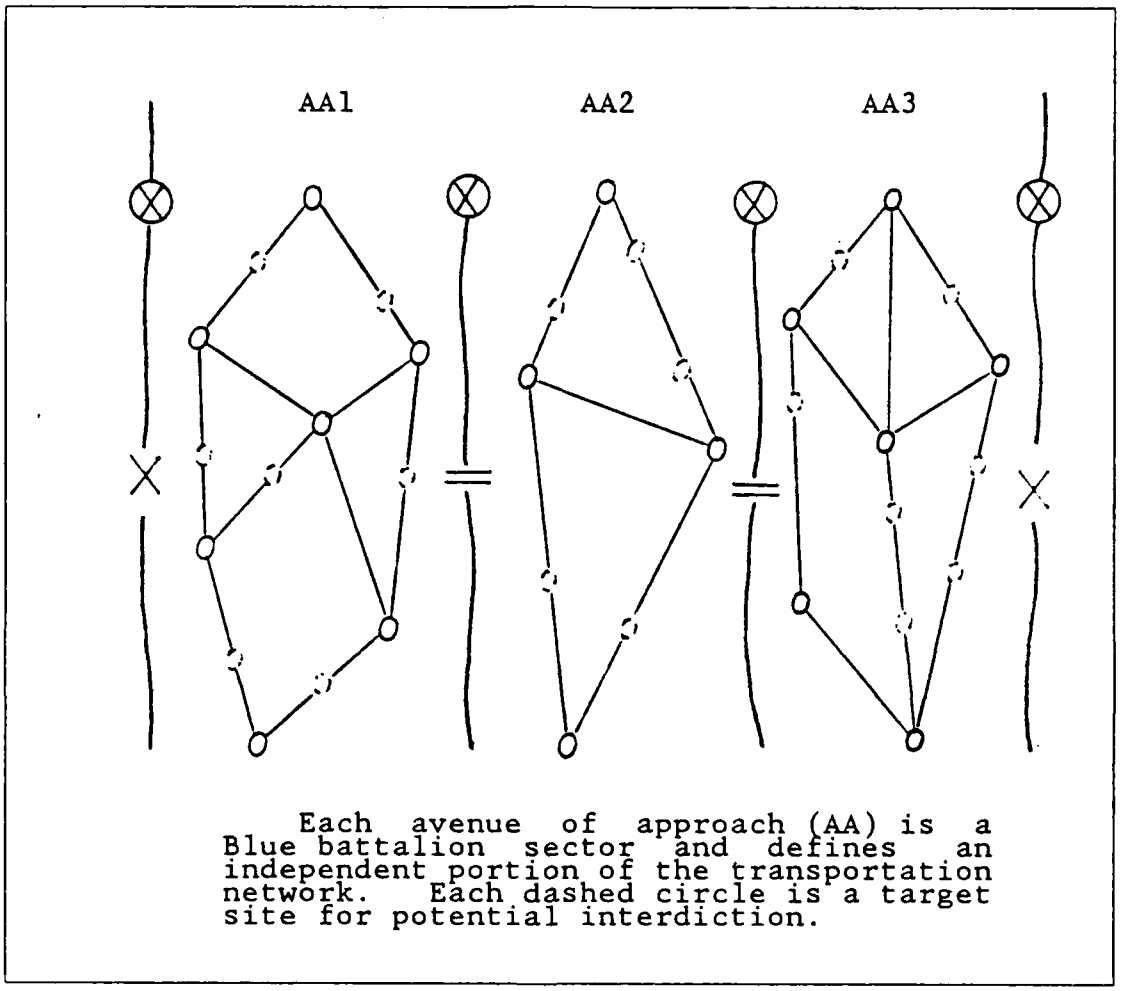

Figure 5.1 Typical Brigade Sector.

3. Enemy Strategies

Types and numbers of enemy forces opposing the brigade and the rules by which strategy can be formed or eliminated must be input to the model. Each Red strategy is

a different assignment of forces to avenues of approach through the battalion sectors. Thus, if a Red motorized rifle division (MRD) contained four motorized rifle regiments (MRR) which are assigned to three avenues of approach, there will be twelve possible assignments, assuming each MRR is indistinguishable from the other. These Red strategies are 3-tuples of integers corresponding to the number of MRRs assigned to each avenue. The first Red strategy might place all four MRRs on the first avenue and would be represented notationally as R(1) = (4,0,0). The second Red strategy, R(2) = (3,1,0), would represent three MRRs on the first avenue and one on the second, and so on. In general, enemy strategies would be k-tuples of integers, where k is the number of avenues of approach through the brigade sector, and where the sum of the integers is equal to the number of enemy subunits in the Red force. The enumeration of Red strategies R(j) can continue for all possible allocations of enemy subunits to avenues.

For the purposes of this model, the Red force allocated to an avenue of approach is treated as a single entity with unique mobility characteristics. Therefore, the minimum time path associated with, for example, three MRRs on a given avenue will in general have a different value that if, say, one MRR were assigned to the same avenue. This distinction permits the model to represent situations where larger forces may move more slowly than smaller forces but may negotiate obstacles more effectively due to the pooling of breaching assets.

Generating strategies by combinatorial enumeration could cause the size of the game to increase beyond the bound of computational feasibility. The potential game matrix can be reduced by excluding from consideration any strategies which are deemed to be "militarily unsound". This amounts to determining a priori which strategies will be

dominated by others in a strategy set. While there is no guarantee that a set of such rules can be found, it may be possible to identify rules which are generally reliable. An example of such a rule might be to exclude from consideration any Red strategy which placed all four MRRs on a single avenue of approach. The rule could reflect the limited ability of the terrain in a single sector to support the movement of an entire division. The generation of such rules is an integral part of the current templating research for the Research Model. There is an obvious tradeoff between computational feasibility and theoretical accuracy which must be resolved by an examination of empirical evidence.

4. Engineer Strategies

The engineer assets available to the brigade must be specified as input to the model. As previously mentioned, each Blue strategy is a unique brigade obstacle plan. This plan is actually composed of a number of smaller network interdiction plans, one for each battalion sector (avenue of approach) within the brigade. Each sector interdiction is determined by the use of the obstacle allocation model presented in Chapter VI. This model iteratively assigns available engineer assets to obstacle sites (targets) along the minimum time path between a source node and a sink node within the sector. Varying the input to the obstacle allocation model causes a new sector interdiction plan to be generated, resulting in a different brigade obstacle plan and hence a different engineer strategy. Within any one game, only the allocation of engineer resources to a sector is varied in enumerating engineer strategies.

Engineer resources which may be allocated to interdict battalion sector networks include assets organic to the engineer company such as the three combat engineer platoons,

and supplemental assets, such as equipment teams and obstacle materials from the parent engineer battalion. To reduce the combinatorial problem of enumerating the possible allocations of resources to sectors, supplemental assets will be aggregated into standardized augmentation packages. One such package might consist of one dozer/loader team, one corps combat engineer platoon, a platoon basic load of obstacle standard packages, and a CEV from the engineer company. The composition and quantity of augmentation packages must be input as data to the model.

Consider a Blue brigade engineer company which consists of three organic platoons and has received one augmentation package. If the brigade sector contains three avenues of approach, there are thirty unique allocations of these four resources to the sectors. This assumes that the three organic platoons are indistinguishable from each other. At this point, Blue engineer strategies could also be represented as 3-tuples, each term specifying the assets to be allocated to an avenue. Let the first Blue strategy be to assign all three platoons and the augmentation package to the first avenue. This can be represented notationally as B(1) = (3+A,0,0); where the 3+A indicates that all assets are allocated to the first avenue. A second strategy can be to assign one organic platoon to each avenue and reinforce the second with the augmentation package; B(2) = (1,1+A,1). In a similiar manner all thirty distinguishable allocations can be enumerated.

Blue strategies could be further extended by considering not only asset-to-sector allocations, but also the Red force against which to plan in each sector. For the case of twelve Red strategies and thirty Blue allocation strategies this fuller enumeration process would result in 360 extended Blue strategies. Such a procedure could be computationally prohibitive for at least two reasons. First, the number of

engineer allocation strategies can grow rapidly as more augmentation packages are made available to the brigade. For example, if another package were available in the previous example the number of Blue strategies would increase by threefold. Second, to generate a payoff for a k sector problem the obstacle allocation model must be employed up to k times (if engineers are to be allocated to all k sectors). Thus, both the potential size of the game matrix and the expense in computing payoff values necessitates the consideration of further simplifying assumptions.

The obstacle allocation model presented in Chapter VI requires that an enemy force be specified for planning purposes. Rather then letting this input vary as a parameter in each Blue engineer strategy, a single generic Red force will be used for the entire game. Thus, if the divisional order to the brigade identified an MRD as the opponent, planning could be done against a "motorized rifle force" as opposed to say, a "tank force". This compromise is not hard to accept, since in reality obstacle plans are predicated primarily on enemy type as opposed to enemy configuration.

5. Aggregation Function

An aggregation function must be specified as input to the brigade engineer planning model. For each possible pairing of opposing engineer and enemy strategies, a single payoff value a(i,j) must be calculated. Minimum enemy transit time through an interdicted sector is the criterion of interest. However, the brigade obstacle interdiction problem will generally contain multiple independent interdiction subproblems, each corresponding to an avenue of approach through the brigade. Thus a scheme to aggregate the several possible minimum transit times into a unique payoff value is necessary. One simplistic approach is to calculate the arithmetic mean of all the minimum transit times. This

method has the advantage that it is easy to calculate and interpret. However, this method loses any information concerning the variance of the transit times, which could be as significant to a military decision maker as the mean value.

An alternative method is to introduce a relative weighting scheme. For a given combination of a Blue strategy B(i) and a Red strategy R(j), weights w(q); q=1 to p, p≤k, can be applied to each of the p expected minimum transit times of the enemy through the brigade, where a Red strategy may use some or all of the k sectors (avenues) within the brigade. The weights would be subject to the constraints:

$$0 \leq w(q) \leq 1 , \quad \sum_{q} w(q) = 1.$$

One approach is to take a weighted average of the sector transit times based on the rank order of those times. Thus, the quickest transit time could be weighted by a factor W(1), the second quickest by W(2), and so on. The number of weights, p, would correspond to the number of sectors which the enemy used in traversing through the brigade. If the division was solely concerned with the minimum time of the first enemy unit exiting the brigade sector, then W(1) would be set to 1 and W(2) through W(p) would be set to 0. If interest was focused on how long the entire enemy force would take to traverse the brigade sector, then the time associated with the slowest unit could be weighted by the factor W(p) = 1.

Another weighting scheme can be based on the percentage of the total Red force that enemy elements on each avenue of approach represent. Such an aggregation can be interpreted as reflecting the conventional military wisdom of "arriving as quickly as possible with as much as possible." Consider an example where a Red motorized rifle

2. Constraints

The following sets of constraints define a feasible solution space for the allocation problem:

a. Asset Availability

$$\sum_{k,t} m(s,k)X(k,t) \leq M(s) \qquad \text{for all } s \qquad (6.1)$$

$$\sum_{k,t} n(r,k)X(k,t) \leq N(r) \qquad \text{for all } r \qquad (6.2)$$

b. Time Feasibility

$$\{Tm(k,t) + Tw(k)\}X(k,t) \leq H \qquad \text{for all } k,t \qquad (6.3)$$

c. Technique Feasibility

$$X(k,t) \leq Z(k,t) \qquad \text{for all } k,t \qquad (6.4)$$

d. Singularity of Target Interdiction

$$\sum_{k} X(k,t) \leq 1 \qquad \text{for all } t \qquad (6.5)$$

3. Arc Time Cost

After each interdiction of a target on an arc (i,j), an additional delay is incurred by a unit traversing that arc. It is assumed that these delays are additive. This implies that each interdicted target has an effect which is independent of the number of such targets the unit has encountered. Thus, enemy resource depletion is not

TABLE 8

Variables

- c(i,j,e) = the time for a type e unit to traverse arc (i,j) prior to interdiction.
- c'(i,j,e) = the time for a type e unit to traverse arc (i,j) after possible interdiction.
- C(k,t) = the utility cost of performing technique k at target t.
- d(k,e) = the delay value associated with employing technique k against a unit of type e. This corresponds to an entry in a delay column in the SOP table.
- D* = the maximum delay value of all remaining interdiction assets at an intermediate stage of plan development.
- H = the duration of the planning horizon.
- m(s,k) = the number of type s systems necessary to perform technique k.
- M(s) = the number of type s units available during the planning horizon.
- n(r,k) = the number of type r resources necessary to perform technique k.
- N(r) = the number of type r resources available during the planning horizon.
- Tm(k,t) = the expected time to move assets to perform technique k at target t.
- Tw(k) = the onsite worktime to accomplish technique k.
- U = an upper bound on V($\underline{X}$).
- V($\underline{X}$) = the magnitude of the minimum path associated with a plan $\underline{X}$.
- X(k,t) = a decision variable which is equal to 1 if technique k is assigned to target t; 0 otherwise.
- $\underline{X}$ = a set of decision variables which describes a unique interdiction allocation plan.
- $\underline{X}^*$ = an optimal interdiction allocation plan.
- Y(k) = the number of times that technique k would have to be employed to maximize the delay value of remaining assets.
- Z(k,t) = a data variable which is set to 1 if technique k is an allowable interdiction method for target t; 0 otherwise.

are targets which represent sites of possible interdiction. Examples of targets would include bridges, tunnels, points on a highway, and terrain constrictions. Engineer forces may interdict some or all of these targets by employing various combinations of systems such as squads and bulldozer teams, and materials such as mines and demolitions. Confronted with limited resources, the obstacle allocation model must make 'intelligent' allocations of resources to targets to best meet the objective of increasing the time for an enemy to traverse a portion of the network. The problem will be confined to identifying an initial assignment of assets within a defined planning period where each target may be interdicted at most once. The definitions of indicies and variables relevant to the problem formulation are found in Tables 7 and 8.

TABLE 7

Indicies

- e = the type of enemy force against which the interdiction plan is to be designed or evaluated. This identifies a delay column in the SOP table.
- k = a technique for interdicting a target. This corresponds to a unique row in the SOP table and identifies how a target is to be interdicted and what the result will be.
- r = a type of material standard package. Examples include bridge demolition and M180 road crater packages.
- s = a type of engineer system. Combat engineer squads and equipment teams represent catagories of systems identified by this index.
- t = a target for potential interdiction. Each target on the network will have a unique value of t.

VI. OBSTACLE ALLOCATION MODEL

A. GENERAL

The purpose of the obstacle allocation model is to specify a feasible allocation plan which supports the countermobility mission of interdicting the transportation network. Once the network interdiction plan has been specified, expected travel times can be determined for units of interest. These times can be used in defining a payoff value for a cell of the game matrix discussed in Chapter V. Input to the model is an array corresponding to a Blue strategy. In addition, the model will access specific data bases such as those which represent the transportation network and the engineer planning SOP table.

The focus of this chapter will be to formulate the engineer resource allocation problem as it relates to the countermobility case. The nature of the objective function will be discussed and a generalized heuristic algorithm will be presented. In addition, the initial structure for a Branch and Bound algorithm will be presented. The chapter will conclude by discussing alternative approaches to the network interdiction problem.

B. PROBLEM FORMULATION

1. Problem Statement

Consider a highway system as it is represented in the Research Model. The transportation system consists of numbered nodes and connecting arcs. Each arc indicates a segment of road or trafficable terrain of uniform characteristics and each node represents a junction. Along each arc

Maximize v

Subject to:

$$19.0x(1) + 14.5x(2) - v \geq 0$$

$$15.5x(1) + 16.0x(2) - v \geq 0$$

$$x(1) + x(2) = 1$$

$$x(1),\ x(2) \geq 0$$

Figure 5.6 Game Formulation.

9. Execution Instructions

The selection of strategy B(1) for Blue determines that the augmentation package will be allocated to the sector containing AA1. The obstacle plan corresponding to this assignment of assets must either be retrieved from temporary storage or the plan must be regenerated by the obstacle allocation model. The Red strategy R(2) is more easily interpreted and the vector (1,1,2) can be sent to the execution module.

		RED(min)	
		R(1)	R(2)
BLUE (max)	B(1)	19.0	15.5
	B(2)	14.5	16.0
	B(3)	14.0	15.5

Figure 5.5 Payoff Matrix.

the game. A check for a saddle point reveals none and thus the game must have a solution in mixed strategies.

7. Game Solution

The solution to the game can be determined by linear programming as previously discussed. The formulation for Blue is shown in Figure 5.6. The solution to this program is x(1)*=.30 and x(2)*=.70 and the value of the game is v*=15.85. The dual to this program yields the Red optimal mixed strategy y(1)*=.10 and y(2)*=.90.

8. Strategy Selection

To select the specific Blue and Red strategies to be transmitted to the execution module it is necessary to sample twice from a pseudo-random number generator. Suppose that this has been done and that the values are u(1)=.1018 for Blue and u(2)=.7365 for Red. Since u(1) falls between 0.00 and 0.30, strategy B(1) is selected for Blue. Similarly, u(2) falls between 0.10 and 1.00 and thus strategy R(2) is selected for Red.

		RED	
		$R(1)$ (2, 1, 1)	$R(2)$ (1, 1, 2)
BLUE	$B(1)$ (1+A, 1, 1)	(28.0, 6, 14)	(20, 6, 18.0)
	$B(2)$ (1, 1+A, 1)	(17.5, 9, 14)	(19, 9, 18.0)
	$B(3)$ (1, 1, 1+A)	(17.5, 6, 15)	(19, 6, 18.5)

Figure 5.4 Enemy Minimum Transit Times.

$$a(1,1): .50(28.0) + .25(6) + .25(14) = 19.0 \quad (5.1)$$

$$a(2,1): .50(17.5) + .25(9) + .25(14) = 14.5 \quad (5.2)$$

$$a(3,1): .50(17.5) + .25(6) + .25(15) = 14.0 \quad (5.3)$$

$$a(1,2): .25(20) + .25(6) + .50(18.0) = 15.5 \quad (5.4)$$

$$a(2,2): .25(19) + .25(9) + .50(18.0) = 16.0 \quad (5.5)$$

$$a(3,2): .25(19) + .25(6) + .50(18.5) = 15.5 \quad (5.6)$$

6. Matrix Scan

A check for dominated strategies reveals that the payoff values associated with B(3) are both less than or equal to all other values in the same columns. Therefore, B(3) is dominated by B(1) and B(2) and may be eliminated from further consideration. No other dominance exists within

2. Strategies

The Red and Blue strategies are 3-tuples representing asset-to-sector allocations and are only partially enumerated due to the issuance of strategy elimination rules. The Red strategies are: R(1)=(2,1,1) and R(2)=(1,1,2). The Blue strategies are: B(1)=(1+A,1,1), B(2)=(1,1+A,1), and B(3)=(1,1,1+A).

3. Obstacle Plans

The obstacle allocation model is employed to produce obstacle plans for each sector in accordance with each Blue strategy. This model is the subject of Chapter VI where an illustrative example considers the development of the sector plan for AA2 under Blue strategy B(2).

4. Minimum Transit Times

The p-tuple of enemy minimum transit times through the battalion sectors are presented in Figure 5.4. Since the Red strategies both employ all 3 avenues of approach, p=k=3 for all cases. The calculation of the second term of the p-tuple (17.5, 9, 14) for the case of R(1) verses B(2) is also presented in the example of Chapter VI.

5. Payoff Values

The aggregation function specified by the input scenario has established equal weights for all the MRRs. Therefore each represents one fourth of the value of the MRD. The following equations specify the payoff values corresponding to each of the 3-tuples in Figure 5.4.
The resulting payoff matrix is presented in Figure 5.5.

5. Calculate a payoff value by applying the aggregation function to the p-tuple of times from Step 4. Repeat Steps 3 through 5 until all m Blue strategies and all n Red strategies are considered.

6. Scan the payoff matrix for dominated strategies and eliminate them from further consideration. Scan again for a saddle point and skip to Step 9 if one is found.

7. Solve the game by linear programming as a maximization problem for Blue and record the optimal strategy vector $\underline{x}^*$. Determine the dual to this formulation and record the Red optimal strategy vector $\underline{y}^*$.

8. Select a pure strategy for Blue by sampling from a uniform(0,1) distribution and comparing the sampled value against the optimal strategy vector $\underline{x}^*$. Repeat this procedure for Red using $\underline{y}^*$.

9. Pass the selected Blue brigade obstacle plan and the Red attack configuration to the Research Model execution module and terminate the algorithm.

F. EXAMPLE

1. Input

Consider again the brigade sector depicted in Figure 5.1 and assume that a delay mission has been issued to the defending force. In 8 hours a Red MRD with 4 MRRs is expected to encounter this sector which is composed of 3 avenues of approach(AA). It is established that AA1 and AA3 can each support at most 2 MRRs while AA2 can support only 1 MRR. The available Blue engineer assets consist of 3 combat engineer platoons each with a basic load of obstacle material, and 1 augmentation package consisting of 1 combat engineer squad with 2 bridge standard packages and 1 dozer team with 2 diesel fuel standard packages. Due to the short preparation time, each of the 3 platoons is to remain in its present sector. However, the augmentation package may be allocated to any of the 3 sectors. The Blue division has determined that each of the MRRs is similarly equipped and is of equal strength.

The concept of dominance may be employed to eliminate from consideration any Red or Blue strategy which is completely dominated by another strategy in the same set. Such a procedure can be done without fear of eliminating useful strategies and may reduce the computational effort necessary to solve the game. Extensive dominance may be common in the situations encountered by the model and thus it may be possible to substantially reduce the average size of the games solved. Similarly, a search for a saddle point may prove to save computational resources if such an occurrence is found to be common within the games formulated.

E. MODEL ALGORITHM

The preceding discussion established the inputs and elements of the brigade engineer planning model. This section is a reiteration which presents the brigade engineer planning model as a sequential algorithm.

1. Receive a brigade countermobility mission and input the time available, each of k sector networks, the enemy forces, strategy elimination rules, engineer assets, and the aggregation function.

2. Determine Red and Blue strategies by enumerating k-tuples of assets and disregarding strategies in accordance with the elimination rules.

3. Determine the brigade obstacle plan for a Blue strategy. First, select one of the k sectors in the brigade and activate the obstacle allocation model to determine a sector plan. This allocation model will require the following input: time horizon, engineer assets alloted to the sector (a term of the Blue strategy k-tuple), the generic Red force against which to plan, and the sector network including all interdictable target sites and arc time cost parameters for the generic force. Second, record the planned interdictions to targets on the sector network. Third, repeat this procedure until all k sectors have been considered.

4. Calculate a p-tuple of enemy minimum transit times through the brigade. First, identify the Red force assigned to a sector. Second, initialize the arc time cost parameters and obstacle delay values to reflect the Red force. Third, calculate the minimum time path through the sector network between designated source and sink nodes. Fourth, repeat this procedure until all p sectors assigned Red units are considered.

		RED(min)						
		R(1)	R(2)	.	.	.	.	R(n)
	B(1)	a(1,1)	a(1,2)	.	.	.	.	a(1,n)
	B(2)	a(2,1)	a(2,2)	.	.	.	.	a(2,n)
	.	.	.					.
BLUE	.	.	.		a(i,j)			.
(max)	.	.	.					.
	.	.	.					.
	B(m)	a(m,1)	a(m,2)	.	.	.	.	a(m,n)

Figure 5.2 Planning Game Matrix.

Maximize v

Subject to:

$$\sum_i a(i,j)x(i) - v \geq 0 \quad \text{for } j = 1 \text{ to } n$$

$$\sum_i x(i) = 1$$

$$x(1), x(2), \ldots, x(m) \geq 0$$

Figure 5.3 Blue Game Formulation.

pure strategies to be implemented. Computational efficiencies may be achieved by exploiting two principles of the TPZS game prior to formulating the linear program.

strategy is selected and a new brigade obstacle plan is determined. This procedure continues until payoffs have been determined for all pairings of B(i) and R(j).

With the strategies enumerated and the payoff values expressed, the game is in normal form. Figure 5.2 illustrates the format of the corresponding game matrix. Blue is the maximizing player since its objective is to delay Red for as long as it can. Conversely, Red is the minimizing player since it seeks to penetrate the brigade as quickly as possible with as much as possible.

2. Solution

The game in normal form can be solved as a linear program as was discussed in Chapter IV. The formulation of this program for Blue is straightforward and appears as Figure 5.3. The solution to this program is v* and $\underline{x}^*$ = x(1)*,x(2)*,...,x(m)*, where the game value v* represents the expected payoff to Blue given that it uses its optimal mixed strategy $\underline{x}^*$. Additionally, the dual to this formulation yields $\underline{y}^*$ = y(1)*,y(2)*,...,y(n)* which is Red's optimal mixed strategy.

The specific course of action which Blue should pursue can now be determined by sampling a pseudo-random deviate from a uniform(0,1) distribution and making an appropriate comparison with the distribution $\underline{x}^*$. Once a pure strategy B(i) has been selected, the brigade obstacle plan which it represents can be transmitted to the Research Model execution module for implementation. Likewise, a pure strategy can be selected for Red by sampling a new pseudo-random deviate and making a comparison against the distribution $\underline{y}^*$.

The procedure outlined above envisions the use of a linear programming routine which is passed the m by n game matrix and which returns the indices for the Blue and Red

The payoff function is more difficult to summarize. It is actually a multiple step algorithm which plans the allocation of Blue engineer assets to interdict sector networks, and evaluates the minimum time path for Red units traversing the sectors. The times corresponding to those paths are aggregated into a single payoff value by the application of an aggregation function. A more detailed discussion of payoff values follows.

For a Blue strategy B(i), the brigade obstacle plan is specified by employing the obstacle allocation model of Chapter VI to assign the assets in B(i) to interdictable target sites. This assignment process is repeated for each of the k sectors in the brigade. A Red strategy R(j) is then paired with B(i), the corresponding terms of each k-tuple constituting an assignment of a Red force consisting of Red subunits against a Blue sector obstacle plan. This assignment identifies enemy and obstacle indices which permit arc time cost parameters and obstacle delay values to be read from Research Model data files. The sector networks are then initialized with these values. The time cost for each arc is the sum of the enemy's travel time were the arc not interdicted, plus the delay times associated with any obstacles assigned to the arc. The minimum time path is determined between source and sink nodes for each sector to which a Red force is assigned. Thus, a p-tuple of times is determined where $p \leq k$. Finally, the proportional value aggregation function is applied to determine the payoff value a(i,j) as a weighted sum of the p-tuple of times.

The process of determining payoff values is continued by pairing the current B(i) against another Red strategy and reinitializing the arc time cost parameters and obstacle delay values to reflect the change in enemy configuration. Once all n Red strategies have been paired against B(i) and payoffs have been calculated, the next Blue

division (MRD) consisting of four motorized rifle regiments (MRR) will negotiate a Blue brigade sector consisting of three avenues of approach. One option would be to place two MRRs on the first avenue and one MRR on each of the last two avenues. Assume that an obstacle plan has been specified for each avenue and that the resulting minimum transit times for the Red units on those avenues are t(1), t(2), and t(3) respectively. Then the payoff could be expressed as the weighted sum:

$$a(i,j) = .50t(1) + .25t(2) + .25t(3)$$

While this method is simple for threats composed of identical subunits, difficulty arises in assigning weights within heterogeneous forces. For example, if the previously mentioned MRD consisted of three MRRs and a tank regiment (TR) the problem of assigning weights is nontrivial since the relative value of a MRR verses a TR is not self evident. This difficulty must be resolved through the establishment of a generalized value system within the Research Model. For the present discussion, the proportional weighting scheme will be employed and weights will be input to the brigade engineer planning model.

D. GAME STRUCTURE

1. Formulation

Having established the relationships which are pertinent to both the Red and Blue forces, it is possible to formulate the allocation planning problem as a TPZS game. The Blue strategies B(i); i=1 to m and Red strategies R(j); j=1 to n each represent a k-tuple asset-to-sector allocation and are determined by the enumeration of possible combinations and the elimination of "militarily unsound" options as previously discussed.

considered. The value of an arc time cost parameter after an interdiction is calculated as follows:

$$c'(i,j,e) = c(i,j,e) + \sum_{k,t} d(k,e)X(k,t) \qquad (6.6)$$

Where: e is as specified by input.
t ranges over the subset of targets on (i,j).

4. Objective Function

Consider the interdiction planning problem where an enemy force will arrive at a local source node u, at the conclusion of a period of duration H. The interdiction planner does not know the specific composition of the enemy force, but it is known that it will be of the generic type, e. The desired objective is to identify from among a set of feasible plans { $\underline{X}$ }, that plan $\underline{X}^*$ which makes as large as possible the minimum time for the enemy to arrive at a local sink node v. That is, the objective is to maximize the minimum time path for a unit of type e from u to v subject to the constraints in Equations 6.1 through 6.5.

Solving for the minimum path from u to v through a network interdicted in accordance with a plan $\underline{X}$ is equivalent to solving a network flow problem where the goal is to send a single unit of flow from source to sink at minimum cost. The cost associated with each arc (i,j) is c'(i,j,e); the time for a type e enemy to traverse the arc following possible interdiction. This standard minimum cost flow problem can be modelled as shown in Figure 6.1 where f(i,j) is a function representing the flow across arc (i,j) [Ref. 18: p. 41].

The first constraint in Figure 6.1 ensures that exactly one unit of flow leaves the source node u. The second set of constraints guarantees that conservation of flow is not violated as the flow moves through the network.

$$\text{Minimize} \sum_{i,j} c'(i,j,e)f(i,j)$$

Subject to:

$$\sum_j f(u,j) - \sum_j f(j,u) = 1$$

$$\sum_j f(i,j) - \sum_j f(j,i) = 0 \quad \text{for } i \neq u \text{ or } v$$

$$\sum_j f(v,j) - \sum_j f(j,v) = -1$$

$$f(i,j) \geq 0 \quad \text{for all } i,j$$

Figure 6.1 Minimum Path Formulation.

The third constraint ensures that the unit of flow arrives at the sink node v. The minimum cost path is that sequence of arcs (i,j) such that f(i,j) = 1.

A conceptual approach to solving the allocation problem would be to enumerate all feasible plans $\underline{X}$, solve the associated minimum path problem for each, and select as $\underline{X}^*$ that plan which has the greatest objective function value $V(\underline{X})$.

While such an approach would identify an optimal plan, it is of little practical value since the number of feasible plans can be quite large. Consider a simplistic problem in which there are 50 targets and 25 technique teams, each of which can interdict any target. Even if one considers only plans which specify full utilization of teams, there are over 126 trillion unique plans to evaluate.

An alternative approach is to construct an algorithm which incrementally allocates assets to interdict targets based on a set of reasonable rules. This heuristic approach is commonly used to resolve the scarce resource problem in project planning activity networks [Ref. 19: p. 155]. While no claim of optimality is made, the method can produce feasible, practical solutions.

C. HEURISTIC ALGORITHM

The purpose of this section is to propose a generalized heuristic algorithm for asset allocation in the countermobility mission and to discuss the nature of the rules which can guide the process. The basic structure of the algorithm is:

1. Initialize the data.
2. Calculate the minimum time path for a force of type e through the network from the source node u to the sink node v.
3. Select and interdict the most cost effective, feasible target on the path from Step 2. If no selection can be made, terminate the algorithm.
4. Return to Step 2.

The algorithm terminates when one of the following conditions is met:

- No feasible technique remains to interdict a target on the minimum path.
- All targets on the current minimum path are interdicted.

Each step in the algorithm will be examined in further detail.

1. Initialization

Several items of data must be available to initialize the procedure. The region of the transportation network to be considered must be defined. In general, this will amount to specifying the local source and sink nodes, u

and v, and the sets of relevant nodes and arcs which are contained in the region. Relevant arcs are those over which an enemy unit of type e could travel. Thus, only a subset of the transportation network is input. All interdictable sites t, and arc time costs c(i,j,e) associated with the subset network are also included. The planning horizon H, and the quantities of system assets M(s) and expendable resource standard packages N(r) are input to the algorithm.

Reference data available through the SOP table will include the sets of technological coefficients m(s,k) and n(r,k), the onsite worktimes Tw(k), and the delay values associated with each technique d(k,e). The set of all expected times Tm(k,t), for moving assets to targets, must be generated and should represent the time for the slowest piece of equipment in the technique team to arrive at a target. A multiterminal shortest chain algorithm which determines the minimum cost route between all pairs of nodes in a network can be used to establish expected lower bounds on these movement times [Ref. 18: p. 53].

2. Minimum Time Path

Initially, the minimum time path through the network can be determined with all arc cost parameters represented by c(i,j,e). Subsequent determinations will use the values c'(i,j,e) as determined by Equation 6.6. Rather than determining the minimum path by solving a linear program as in Figure 6.1, it is frequently more computationally efficient to employ a labeling procedure such as Dijkstra's algorithm [Ref. 18: p. 46]. This method systematically explores a network from source to sink node assigning a temporary label at each node which represents the direct cost from the source to that node. As it is determined that a node belongs to the minimum path, its label becomes permanent. When the sink node is permanently labeled, the algorithm terminates and all nodes with permanent labels are on the minimum path.

3. Target Selection

Once a path has been selected by Step 2, a search is made for all targets on the arcs associated with the path. If there are no targets available for interdiction on the current minimum path, the algorithm terminates.

Several heuristics can be proposed to guide target selection. The development of a scheme which could enable cost comparisons between alternatives would be highly desirable since target selection could be based on a benefit-cost ratio. Any reasonable measure of cost could be considered. Each technique k has associated with it the number of systems and resource packages necessary to perform it. In addition, the onsite worktime is known. These factors, combined with the travel time to arrive at the worksite, offer several measures of resource cost. Other measures, such as man-hours or equipment-hours, can be derived from them. A utility function can be expressed to transform these dissimilar costs into a common unit of measure. The number of 'utiles', C(k,t), would then be the cost of performing technique k at target t.

A greedy heuristic can be formulated which selects for interdiction by technique k, that feasible target t on the current minimum path which has the largest ratio of delay value d(k,e) per utile cost C(k,t). An alternative would be to consider the effect an interdiction would have on the subsequent minimum path. In this case, a tentative new minimum path would need to be determined for each target/technique pair under consideration. An effectiveness measure could then be the change in minimum path magnitude per utile cost.

The construction of the utility cost function could also take into account other factors such as range to the target. The weighting could be adjusted to favor those

targets within direct fire antitank weapons range, or alternatively, those targets at the maximum range of air and artillery effectiveness.

The feasibility of any interdiction can be checked by temporarily assigning a null valued X(k,t) a value of 1 for the k,t pair under consideration. If none of the constraint sets in Equations 6.1 through 6.5 are violated, the interdiction is declared feasible at a given iteration and is recorded. The value of X(k,t) would then be reset to 0, and the next k,t pair would be considered. If it is determined that no feasible techniques exist for interdicting any of the targets on the current minimum path, the algorithm is terminated.

The k,t pair which is both feasible and best meets the chosen selection criterion is identified and the value of X(k,t) is assigned a permanent value of 1. The algorithm then returns to Step 2, the values of c'(i,j,e) are updated, and a new and possibly different minimum path is determined.

4. Algorithm Variations

Two variations to the proposed algorithm might be considered for inclusion. The first would alter the stated objective to include the possibility of interdicting feasible targets not on the minimum path. This could be done when engineer assets remained after all feasible interdictions to the minimum path were accomplished. Targets on successively longer paths could be considered until all assets were exhausted or all targets had been considered. One justification for such a procedure could be to increase the likelihood that the minimum path route would be selected by the enemy. This could work to the benefit of a defending force if it reduced uncertainty concerning the attacking force course of action.

A second variation could establish a swapping procedure which would exchange targets selected for interdiction with those not selected if such a trade resulted in an increase in the minimum path. This procedure would be applicable if uninterdicted targets existed on the current minimum path which could be interdicted by assets assigned elsewhere. Once a k,t match was established, the values of the two X(k,t) variables could be temporarily exchanged and the resultant minimum path evaluated. If there was an improvement, the exchange would become permanent. Otherwise, the X(k,t) values would revert to their prior magnitudes. The Center for Naval Analyses (CNA) has incorporated this concept into a network interdiction model [Ref. 20: p. 12].

D. EXAMPLE

This section illustrates the interdiction of a sector network by use of the heuristic algorithm discussed in the previous section. The scenario is as was described in the example of Chapter V. Part I of this example develops the obstacle plan for AA2 under Blue strategy B(2) by planning against a generic enemy force, e=1. Part II evaluates the enemy minimum transit time through the sector for the case of R(1) verses B(2) where e=2.

1. Part I: AA2 Obstacle Plan

a. Initialization

Several items of data are required from the brigade engineer planning model to initialize the obstacle allocation model. The sector network corresponding to AA2 is input and appears as Figure 6.2. Node 1 is specified as the source and node 4 as the sink. The generic enemy force e=1 has been specified for planning purposes and the arc time cost parameters (in hours) reflect this selection.

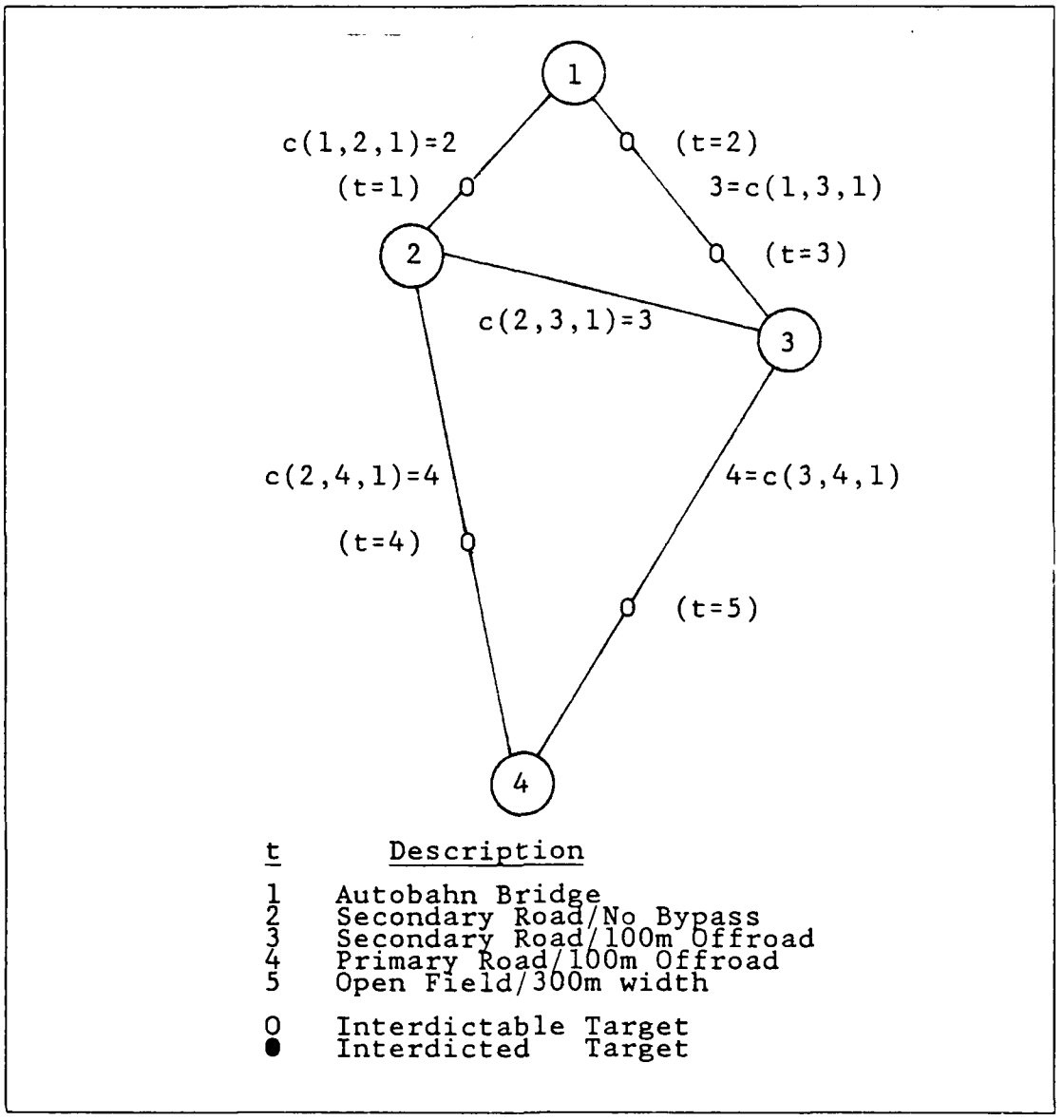

Figure 6.2 AA2: Initial Network (e=1).

Figure 6.2 also depicts the location and type of interdictable target sites on the network, t=1 to t=5. The planning horizon H is equal to 8 hours. Blue strategy B(2) specifies that one organic engineer platoon and one augmentation package be allocated to AA2. The composition of these assets is listed in Table 9.

TABLE 9

Asset Composition

Resources Available:

1 organic platoon + 1 augmentation package

s:	System	M(s):	Qty	r:	Material	N(r):	Qty
1	squad	3+1 =	4	1	bridge	3+2 =	5
2	dozer team	0+1 =	1	2	M180	2+0 =	2
				3	MFJ	1+0 =	1
				4	MOPMS	1+0 =	1
				5	Diesel	0+2 =	2

TABLE 10

Movement Times and Utile Costs

Z(k,t):	t= 1	2	3	4	5	Tm(k,t)	C(k,t)
k=1	1	0	0	0	0	4	8
2	0	0	0	1	0	2	7
3	0	1	0	0	0	6	1
4	0	1	0	0	0	6	2
5	0	0	1	0	0	5	6
6	0	0	0	0	1	1	15
7	0	0	0	0	1	2	3

The allowable interdictions Z(k,t), and relevant movement times Tm(k,t) and utile costs C(k,t) are enumerated in Table 10. Reference data such as technological coefficients m(s,k) and n(r,k), onsite worktimes Tw(k), and delay values d(k,e) are specified in the abbreviated SOP table presented as Table 11. Finally, the values X(k,t); k=1 to 7, t=1 to 5 are initialized to 0.

TABLE 11

SOP Table (Abbreviated)

k	Task	s	m(s,k)	r	n(r,k)	Tw(k)	d(k,e) e=1	d(k,e) e=2
1	Blow Bridge (Autobahn)	1	1	1	4	3	3.0	6.0
2	Block Road (Primary/100m)	1	2	2	2	2	1.0	2.0
3	Block Road (Secondary/0m)	1	1	2	1	1	1.0	3.0
4	Block Road (Secondary/0m)	1	1	2 4	1 1	1.5	1.5	4.0
5	Block Road (Secondary/100m)	1	1	2 3	1 1	4	1.5	2.5
6	Block Field (Open/300m)	1	3	3	3	3	1.0	1.5
7	Block Field (Open/300m)	2	1	5	3	4.5	.5	.5

b. Iteration 1

Once the data has been initialized, the minimum path through the current network from node 1 to node 4 is determined. Inspection of Figure 6.2 reveals that this path is (1,2), (2,4) which has a value of 6 hours. Targets t=1 and t=4 are the uninterdicted targets on the current minimum path. The selection procedure examines each allowable technique for interdicting these targets to establish that constraints 6.1 through 6.5 are satisfied. Once feasibility is established, the delay/cost ratio d(k,e)/C(k,t) is evaluated. The feasible interdiction (k,t) which has the largest delay/cost ratio is selected for inclusion in the obstacle plan and X(k,t) is permanently set to 1.

The first target to be considered is t=1. An examination of Table 10 shows that k=1 is the only allowable interdiction technique for t=1. Thus, X(1,1) is temporarily assigned a value of 1 to test the feasibility of this interdiction. Substitution of k=1, s=1, t=1 into constraint 6.1 and reference to Table 9 and Table 11 yields:

$$m(1,1)X(1,1) \leq M(1) \qquad (6.7)$$

where m(1,1)=1 and M(1)=4. Since s=1 is the only system asset required by k=1, it is not necessary to test the constraint for s=2. Thus constraint set 6.1 is satisfied. Similarly, substitution of k=1, r=1, t=1 into constraint 6.2 yields:

$$n(1,1)X(1,1) \leq N(1) \qquad (6.8)$$

where n(1,1)=4 and N(1)=5. This is the only resource constraint that must be checked for k=1 and so constraint set 6.2 is also satisfied. The time feasibility of the

interdiction is checked by constraint 6.3 which becomes upon substitution:

$$\{Tm(1,1) + Tw(1)\}X(1,1) \leq H \qquad (6.9)$$

where Tm(1,1)=4, Tw(1)=3, and H=8. Thus, the interdiction is time feasible. Technique allowability is established by reference to Table 10.

$$X(1,1) \leq Z(1,1) \qquad (6.10)$$

Thus, constraint 6.4 is satisfied. Finally, Singularity of target interdiction is established by constraint 6.5. Since only X(1,1) has a value of 1 at present, the sum over all k of X(k,1) is equal to 1.

$$X(1,1) \leq 1 \qquad (6.11)$$

All constraints 6.1 through 6.5 are satisfied and X(1,1) is declared a feasible interdiction. The delay/cost ratio for this interdiction is calculated by referring to Table 11 where d(1,1)=3.0, and to Table 10 where C(1,1)=8.0.

$$d(1,1)/C(1,1) = 3.0/8.0 = .375 \qquad (6.12)$$

The temporary value of X(1,1) is reset to 0 and the next target is considered.

Reference to Table 10 establishes that target t=4 may only be interdicted by technique k=2. The interdiction X(2,4) can be shown to be feasible by substitution into the constraints 6.1 through 6.5 as was done for the previous target. (Note that two inequalities must be satisfied for constraint set 6.2 since two resources r=2 and r=3 are

involved in technique k=2.) The delay/cost ratio for this interdiction is:

$$d(2,1)/C(2,4) = 1.0/7.0 = .143 \qquad (6.13)$$

At this point all feasible techniques for interdicting the current minimum path have been considered. Since .375>.143, target t=1 is selected for interdiction by technique k=1 and X(1,1) is permanently set to 1. The new time cost parameter for arc (1,2) is determined by substitution into Equation 6.6.

$$c'(1,2,1) = 2 + \{(3.0)(1)\} = 5 \qquad (6.14)$$

The sector network is updated and appears as Figure 6.3.

c. Iteration 2

Reference to Figure 6.3 reveals that the new minimum path from node 1 to node 4 is (1,3), (3,4) which has a value of 7 hours. The targets available for interdiction on this path are t=2, t=3, and t=5. Target t=2 will be considered first.

Inspection of Table 10 shows that target t=2 must be considered for interdiction by both techniques k=3 and k=4. In examining the feasibility of interdictions, it must be recalled that X(1,1) has been set to 1 and thus some assets are already committed to target t=1. The system asset feasibility check for k=3, t=2 is:

$$m(1,1)X(1,1) + m(1,3)X(3,2) \leq M(1) \qquad (6.15)$$

which becomes upon substitution:

$$(1)(1) + (1)(1) \leq 4 \qquad (6.16)$$

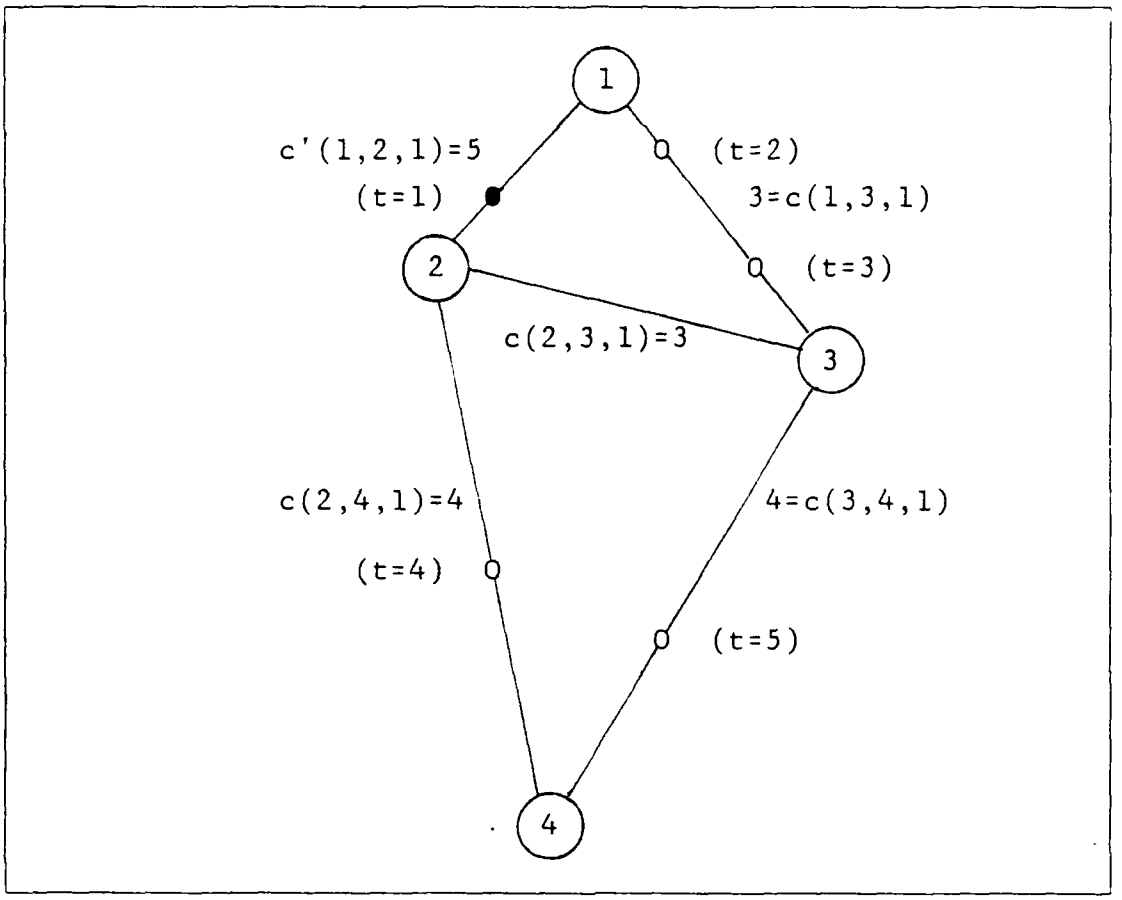

Figure 6.3 AA2: First Interdiction.

Subsequent checks on constraints 6.2 through 6.5 confirm that k=3 is a feasible interdiction technique for t=2. The delay/cost ratio is:

$$d(3,1)/C(3,2) = 1.0/1.0 = 1.0 \qquad (6.17)$$

Examination of the case k=4, t=2 establishes that no constraints 6.1 through 6.5 are violated. The delay/cost ratio is:

$$d(4,1)/C(4,2) = 1.5/2.0 = .75 \qquad (6.18)$$

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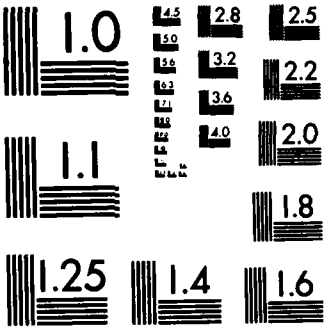

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Target t=3 may be interdicted by technique k=5. However, an evaluation for feasibility reveals that constraint 6.3 is violated since

$$\{Tm(5,3) + Tw(5)\}X(5,3) \leq H \qquad (6.19)$$

becomes upon substitution:

$$\{ 5 + 4 \}(1) > 8. \qquad (6.20)$$

Thus, the interdiction X(5,3) is declared time infeasible and no delay/cost ratio need be calculated for this case.

The final target for consideration on the current minimum path is t=5. Table 10 shows that both k=6 and k=7 are allowable interdiction techniques. Feasibility checks for k=6, t=5 show that constraint 6.2 is violated since

$$n(3,6)X(6,5) \leq N(3) \qquad (6.21)$$

becomes upon substitution:

$$(3)(1) > 1. \qquad (6.22)$$

The interdiction X(6,5) is declared resource infeasible since technique k=6 requires 3 MFJ minefield standard packages and there is only one available. In the same manner the interdiction X(7,5) is declared resource infeasible since constraint 6.2 is violated. Technique k=7 requires 3 diesel standard packages and only 2 are available.

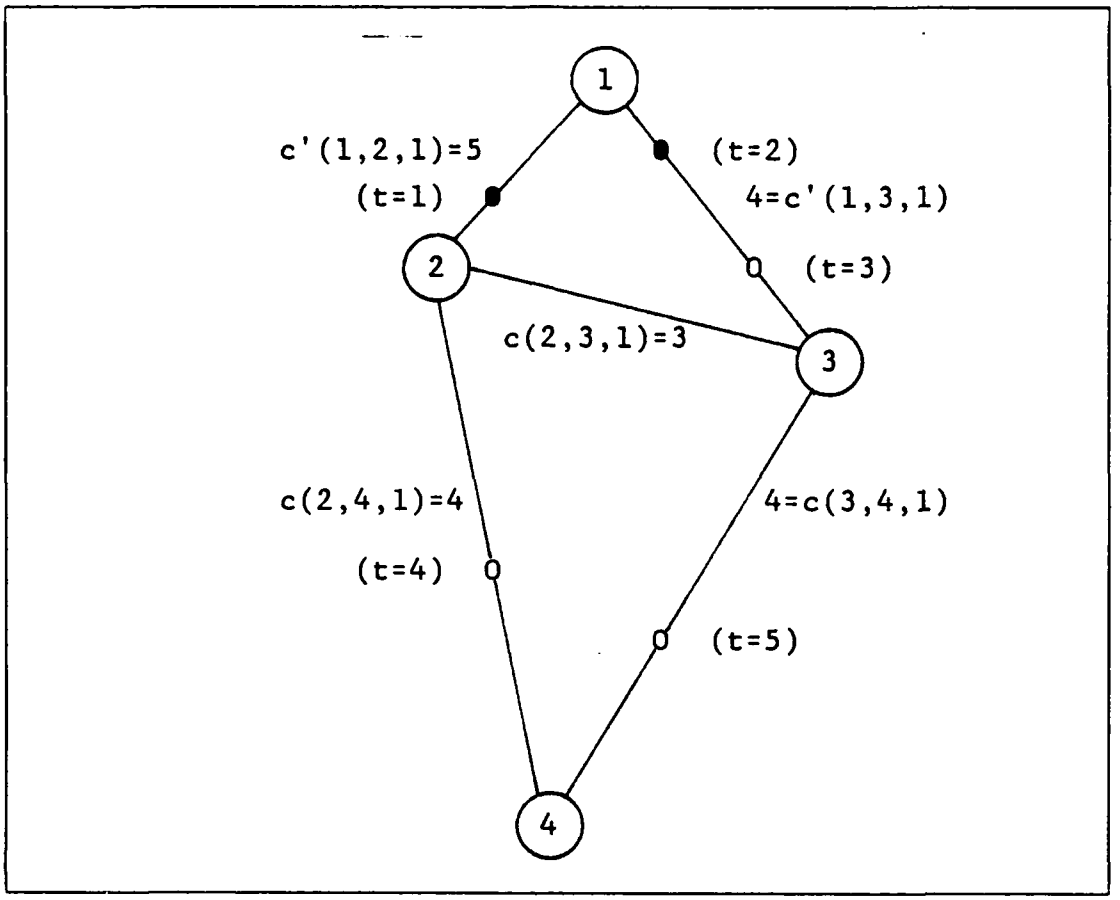

Figure 6.4 AA2: Second Interdiction.

Target t=2 is the only feasible interdiction site on the current minimum path. Based on the delay/cost ratios, (1.00 > .75), k=3 is selected as the interdiction technique and X(3,2) is permanently set to 1. The modified arc cost parameter for arc (1,3) becomes:

$$c'(1,3,1) = 3 + \{(1.0)(1)\} = 4. \qquad (6.23)$$

The sector network is again updated and appears as Figure 6.4.

d. Iteration 3

It is evident from Figure 6.4 that the new minimum path from node 1 to node 4 is again (1,3), (3,4) which now has a value of 8 hours. The uninterdicted targets on this path are t=3 and t=5. However, t=3 was shown to be infeasible at Iteration 2 as was t=5. Thus, there are no feasible interdictions to the current minimum path and the algorithm terminates. The obstacle plan for this sector is $\underline{X}$ = { X(1,1)=1, X(3,2)=1 }. The remainder of this example will calculate the effect of this obstacle plan against an enemy force of type e=2.

2. Part II: Evaluation

Part I of this example developed an obstacle plan for AA2 by utilizing the assets allocated by Blue strategy B(2) and by planning against a generic enemy of type e=1. This portion of the example will evaluate the expected minimum transit time of an force of type e=2 through this interdicted network. It is emphasized that the obstacle plan from Part I, $\underline{X}$ = { X(1,1)=1, X(3,2)=1 } remains in effect. However, the arc time costs c(i,j,e) and delay values d(k,e) will change to reflect the mobility characteristics of the type e=2 force.

Recall that Equation 6.6 expresses the value of the arc time cost parameter for an arc (i,j) after possible interdiction. To evaluate the sector network against an enemy force of type e=2 it is necessary to read values of c(i,j,2) from Research Model data files and d(k,2) from Figure 11.

With the plan from Part I still in effect, the values of c'(i,j,2) are determined by Equations 6.24 through 6.28. The corresponding network is shown in Figure 6.5. The minimum path through this network is (1,3), (3,4) which has a value of 9 hours as was stated in Chapter V.

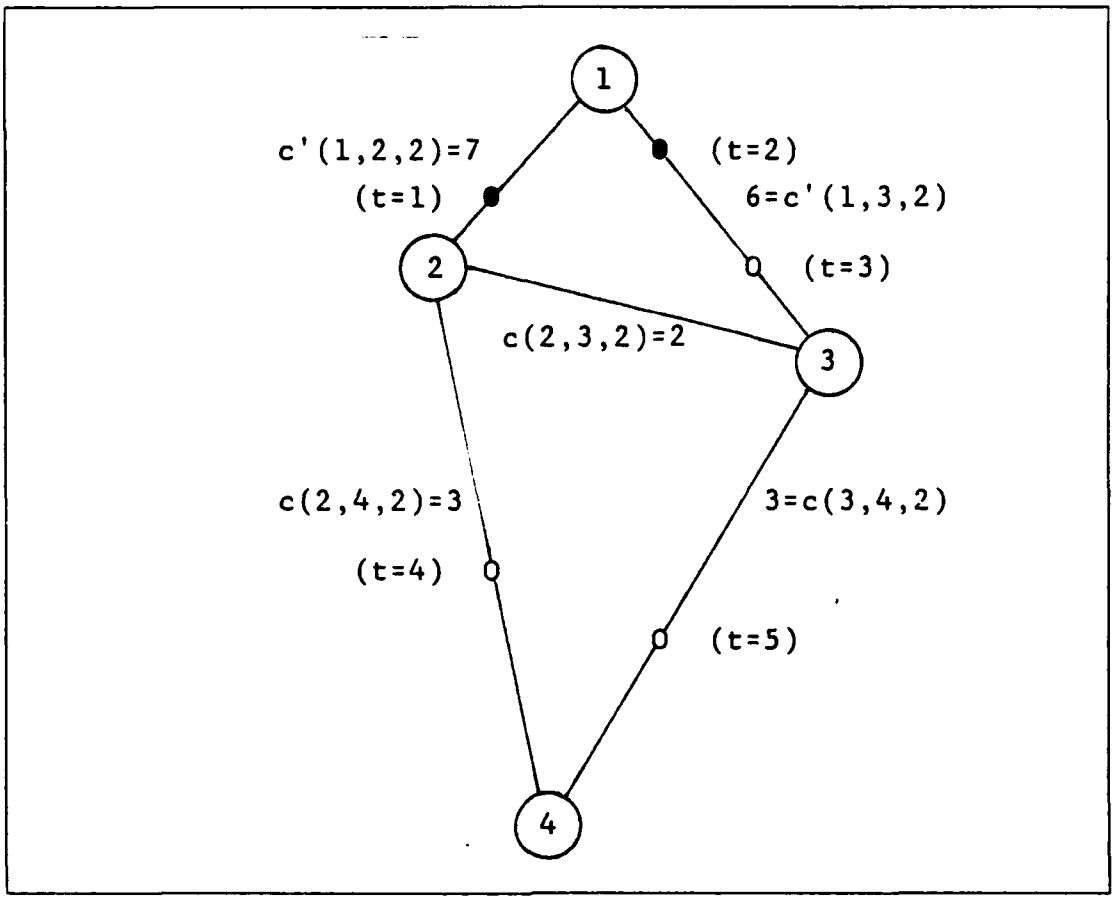

Figure 6.5 AA2: Evaluation (e=2).

$$c'(1,2,2) = 1 + \{ (6.0)(1) \} = 7 \qquad (6.24)$$

$$c'(1,3,2) = 3 + \{ (3.0)(1) \} = 6 \qquad (6.25)$$

$$c'(2,3,2) = 2 + \{ 0 \} = 2 \qquad (6.26)$$

$$c'(2,4,2) = 3 + \{ 0 \} = 3 \qquad (6.27)$$

$$c'(3,4,2) = 3 + \{ 0 \} = 3 \qquad (6.28)$$

E. BRANCH AND BOUND

It was previously mentioned that explictly enumerating all plans $\underline{X}$ and evaluating them for optimality was computationally infeasible for most problems of practical significance. While this is true, it is generally not necessary to conduct such an exhaustive search if a set of reliable rules can be developed which exclude from consideration subsets of solutions which cannot contain the optimum. The method of Branch and Bound (BB) accomplishes this [Ref. 19: p. 201]. BB follows a heuristic tree search in which the space of feasible solutions is systematically searched until the optimum is reached. BB alternately applies two operations; subset formation and subset elimination. The first forms new subsets of alternatives while the second eliminates subsets from futher consideration. At the conclusion of the procedure, each point in the solution space will have been either explicitly or implicitly enumerated. The utility of BB depends on the selection of good rules which make as small as possible the number of points which must be explicitly enumerated. [Ref. 19: p. 201]

1. Rules

To apply BB to the network interdiction problem, three guiding rules will be established.

1. Only feasible interdictions should be considered at each step of the enumeration process, since only feasible allocation plans can be optimal.
2. As resources are successively applied to the network to form an allocation plan $\underline{X}$, either at least one feasible target on the current minimum path will be interdicted in a subsequent version of the current plan, or the present plan and all its successor plans cannot be optimal.
3. An upper bound on the value of a plan $V(\underline{X})$ can be obtained at each step of the enumeration by adding to the value of the current minimum path, an upper bound on the delay causing potential of all remaining assets.

The first rule may appear trivial, but it is useful since the problem has well defined criteria for feasibility. Thus, rather than only considering whether a given k,t pairing is allowable, the addition of another target to the interdiction plan $\underline{X}$ can be conditioned on which targets have already been added to the plan.

The second rule in essence states that if something can be done to increase a minimum path(s), then something must be done or else the plan will be non-optimal and may be discarded. For example, any plan which ignored feasible targets on the first most minimum path through a network would always have a value $V(\underline{X})$ which was equal to the magnitude of that path, irrespective of how many resources were directed against targets elsewhere.

The third rule is derived from the fact that the ability to influence the minimum path is limited by resources. The largest such a path could become is a function of the magnitude of the sum of the delay values d(k,e) of an optimal mix of the remaining assets, and the magnitude of the current minimum path. Due to target/technique incompatibility, it is unlikely that the resources could be employed to produce their maximum delay benefit. However, the formation of an upper bound is useful in eliminating subsets of solutions from consideration.

One can obtain the maximum delay value of all uncommitted resources for a current version of a plan $\underline{X}$ by relaxing the target/technique compatibility requirement and solving a linear program. This divorces resource delay potential from the network and the difficult combinatorics problem it represents. The formulation of the linear program is given in Figure 6.6

Let D^* be the optimal value of the objective function in Figure 6.6, and $\underline{X}$ the current version of a plan. Then an upper bound U on the maximum value of the minimum

Maximize $\sum_k d(k,e)Y(k)$

Subject to:

$$\sum_k m(s,k)Y(k) \leq M'(s) \qquad \text{for all } s$$

$$\sum_k n(r,k)Y(K) \leq N'(r) \qquad \text{for all } r$$

$$Y(k) \geq 0 \qquad \text{for all } k$$

Where:

e is fixed as per input.

$$M'(s) = M(s) - \sum_{k,t} m(s,k)X(k,t) \quad \text{for all } s$$

$$N'(r) = N(r) - \sum_{k,t} n(r,k)X(k,t) \quad \text{for all } r$$

Y(k) = the number of times that technique k would have to be employed to maximize the delay value of the remaining resources M'(s) and N'(r).

Figure 6.6 Maximum Delay Value Formulation.

path in any plan which includes the interdicted targets in $\underline{X}$ can be found from Equation 6.29.

$$U = D^* + V(\underline{X}) \tag{6.29}$$

2. Procedure

The three rules can now be used to outline a general procedure for employing the BB technique which is presented as a sequential algorithm.

1. Calculate a minimum path through the network. Record its value $V(\underline{X})$ which is a lower bound on optimality. Calculate an upper bound U from Equation 6.29 and record it. These values are ascribed to the root node of the search tree.

2. Branch by considering each feasible way of interdicting each target on the minimum path. This step incorporates both Rules 1 and 2 , and creates new nodes. Each node corresponds to adding one feasible interdiction to the predecessor plan. If no such additions are possible, the node is said to be fathomed. Other nodes on which a branching can occur are said to be live.

3. Calculate new minimum paths for each new node and record these lower bounds. Reapply Equation 6.29 to determine upper bounds.

4. Scan all the lower bounds and call the greatest lower bound the incumbent. It is the best solution thus far. If at any time the upper bound of a node is equal to its lower bound, the node is fathomed. Further, if the upper bound of any node is less than the value of the incumbent, the node is fathomed and the plan represented by that node and any of its possible successors are declared non-optimal.

5. Go to Step 2 and branch on all live nodes. If no live nodes exist, the value of the incumbent is the optimal value $V(\underline{X}^*)$ and the corresponding plan(s) is(are) globally optimal.

3. Additional Rules

Prior to implementing a Branch and Bound algorithm, considerable research must be directed toward identifying rules to speed the enumeration process. The approach outlined above represents a simplistic application which may not prove to be computationally feasible. A successful algorithm must establish tight bounds on optimality by closely examining the inherent structure of the problem.

Variations on the proposed algorithm may be considered in future research. For example, rather than simultaneously branching on all live nodes as in Step 5, a 'depth first' search could specify branching on that live node which had the greatest upper bound, since it might be considered most likely to contain the optimum. This branching would continue on successor nodes to the current node until a node had been fathomed. The search would then

backtrack up the search tree until the first live node was encountered. The branching could then resume, again choosing a successor node with the greatest upper bound at each branching step. As before, the process would terminate when no live nodes existed.

F. ALTERNATIVE MODELS

Previous models for interdicting transportation networks generally have used concepts other than delay as a criteria. Often the network consists of capacitated arcs and the objective usually focuses on minimizing the maximum flow through the network by identifying the minimum cut set. Flow often represents a measure such as tons of logistics per day. A cut set is defined as a set of arcs which, when removed, divides the network into two sub-networks; one containing the source node, the other the sink node. The value of a cut set is defined to be the sum of the capacities of the arcs in the cut set. The maximum flow-minimum cut theorem states that the maximum flow possible through a network, from source to sink, is equal to the value of the minimum cut set [Ref. 18: p. 149].

Algorithms were proposed by Mustin [Ref. 21] and Nugent [Ref. 22] for allocating airstrikes to interdict a network by targeting arcs comprising a minimum feasible cut set. No consideration was given to the repair times required to restore arc capacities.

Wollmer [Ref. 23] considered the problem of targeting interdictions for the purpose of maximizing the costs associated with maintaining a given level of flow through a network. Costs were assumed to be linear or piece-wise linear functions of flow.

Sullivan [Ref. 24] proposed a method of maximizing transit time through a network by selecting arcs for air

interdiction. Arc parameters were replaced by time dependent functions once interdicted. An algorithm was detailed which determined the best interdiction site at each iteration. The algorithm was open-ended having no established termination criteria.

A more recent model is the Network Interdiction Model / Decision Support System (NIM) developed by CNA [Ref. 20]. NIM is an interactive model which was designed to aid interdiction planners. It permits a selection of three objective criteria; maximum delay, greatest reduction of maximum flow, and least accumulated flow over a specified period. The model extracts target information from the Defense Intelligence Agency data base and produces engineering data based on a procedure developed by the U. S. Army Corps of Engineers, Engineer Study Group. The model uses a heuristic method of target selection and employs efficient implementations of network evaluation algorithms. The similarities between NIM and the present research effort suggest that a close examination of the operating structure of NIM may desirable.

VII. SUMMARY AND FUTURE DIRECTIONS

A. SUMMARY

It is evident that the combat engineers within a corps and division comprise a highly heterogeneous system with multidimensional missions. A unifying factor is that most combat engineer effort is directed at modifying terrain for tactical advantage. Time has been hypothesized as a relevant decision criterion for evaluating the contribution of engineer effort, especially as it relates to the movement times of tactical units through a transportation network. Maximizing the minimum time path through a network can be a desirable countermobility objective since it provides a solution which establishes an expected lower bound on enemy transit times. Such a result compliments the overall game theoretic decision structure which can be employed to optimize the expected payoff to a unit.

A brigade engineer planning model was developed which employs a TPZS game as a decision structure to select courses of action from among sets of possible resource allocation alternatives. The procedure is a sub-optimization since only a limited range of options are considered.

Two methods for approaching the resource allocation problem in the countermobility case were discussed. An incremental heuristic algorithm, called the obstacle allocation model, was developed which successively interdicts the minimum time path at each iteration until no further such interdictions can be accomplished. The method relies on a set of rules to choose the minimum path target which is the most "cost effective" in view of a utility function designed to permit cost comparisons among unlike resources.

A second approach considered the initial structure of a Branch and Bound algorithm to identify an optimal allocation plan. In this approach, relative resource cost was not considered. The optimal solution was defined to be that allocation of available assets which maximized the minimum path through the network. Three rules were proposed to guide the process. Addition rules must be identified to make the method practical.

B. FUTURE DIRECTIONS

Several areas for future research are necessary for the development of an operational engineer planning module. An extensive data base corresponding to the concept of an SOP table must be established. Much of the information required, such as construction times and material requirements, is available in engineer doctrinal literature; with skill manuals, field manuals and unit test and evaluation material being excellent sources. Other data will be more difficult to obtain. For example, delay values associated with standard obstacles must be determined for a wide range of potential threats. Development of these planning estimates will be complicated by the difficulty of obtaining extensive threat performance data.

Further research must be conducted to establish the feasibility of dynamically generating sets of game strategies within the model. The determination of a game theoretic optimal solution is itself a significant computational problem. However, creating the space of alternatives from which the solution is to be selected is a major research challenge. It may become necessary to establish windows for human interaction with the Model to support this need.

Heuristics must be chosen for the target selection procedure of the network interdiction algorithm. In

particular, the notion of resource cost must be formulated through the development of a utility function. As previously discussed, several types of cost may be considered for inclusion.

Research should be directed at establishing additional rules to guide the branch formation and elimination processes of the Branch and Bound algorithm. The successful implementation of this technique requires that the fewest possible number of nodes be explicitly enumerated. Tight bounds on optimality conserve the computational resources which must be dedicated to the problem, while loose bounds do little to exclude subsets of solutions from explicit consideration.

An enhancement of the current allocation model would formulate the problem to include multiple time periods and asset locations. The present model considers only an initial allocation of assets from a common resource pool.

The resource allocation problem must be formulated to support the mobility mission. Of immediate interest will be the selection of an objective function. One option is to consider directing engineer effort toward that path which provides the quickest route for the currently supported unit. Another option is to identify the path which can become the minimum time path through the network once all engineer activity has been completed. This method considers subsequent users of the route and is related to the general engineering mission of developing the infrastructure of the battle area.

The development of a generalized value system for the research model will permit the explicit consideration of the survivability and general engineering mission areas. Its development should also be readily adaptable to mobility and countermobility missions, since the value system as currently envisioned will employ the concepts of time and time discounting to impute values to supporting units.

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