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Assessing Resource Value and Relationships between Objectives in Effects-Based Operations

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ASSESSING RESOURCE VALUE AND RELATIONSHIPS BETWEEN OBJECTIVES IN EFFECTS-BASED OPERATIONS

THESIS

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Abstract

The purpose of this research was developing techniques to calculate the value of a resource within the context of campaign objectives, to identify competing objectives, and to identify conflicting objectives to improve a commander's ability to allocate limited resources. A methodology was developed to express a campaign's objective hierarchy in terms of a set of desired end states for the campaign's system of systems. Value theory was used to identify the resource's value in terms of the direct and indirect effects that are produced to achieve the campaign's objectives. Binding resource constraints within an integer program were used to identify the objectives that competed for the simultaneous use of limited resources. Conflicting objectives were identified using interaction tables. Collectively, the research translated doctrinal, effects-based operational concepts into actionable processes within deliberate planning and crisis action planning horizons.

To my wife, daughter, and son

Acknowledgments

I would like to thank Jesus Christ for granting me the strength to succeed, the never-ending love and support of a wonderful family, and the honor to serve this great nation. Words cannot express how thankful I am for my wife and kids. They never grumbled during the past few months despite constantly hearing "I can't do that right now. I am working on my thesis." I could have never finished this program without them.

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I would also like to thank my GOR-06M classmates for countless smiles, selfless service, and unique leadership opportunities. I pray that the Lord continues to "guard and guide them" and allows our paths to cross frequently.

Robert "Dan" Jones

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ASSESSING RESOURCE VALUE AND RELATIONSHIPS BETWEEN OBJECTIVES IN EFFECTS-BASED OPERATIONS

1. Introduction

1.1. Background

1.1.1. History

Throughout the last half of the 20th century, US foreign policy and national security concerns were fairly rigid. Military force development and campaign planning focused on a Major Theater War (MTW) between symmetric forces. According to Mann, Endersby and Searle, military leaders and planners viewed all conflicts under a "conquest paradigm" (Mann and others, 2002:14). Within this context, military conflicts resulted from diplomatic and political failures.

The resulting goal of military action was destroying the opposing military forces. The three authors state that "[u]nder this paradigm, any target that makes sense militarily can and should be attacked and destroyed" (Mann and others, 2002:14). Hence, campaign planning was accomplished using a target-based approach. This approach reached its apex in Operations DESERT SHIELD and DESERT STORM using a five-ring concept developed by retired Colonel John Warden.

Warden stated that the outcome of warfare was the direct result of the physical means and the morale of the combatants (Warden, 1995:2). He focused on reducing or eliminating an enemy's physical means since physical systems are measurable and morale is harder to measure (Warden, 1995:2). Using his five-ring model, he defined the enemy in terms of its leadership, organic essentials, infrastructure, population, and forces

(Warden, 1995:4). Target sets were built for each ring, were linked to campaign objectives, and formed the foundation for planning, execution, and assessment of operations. By simultaneously striking targets within each ring, an activity termed "parallel warfare," Warden believed one would eventually cause "…the enemy [to] decide to adopt our objectives, or make it physically impossible for [an enemy] to oppose us" (Warden, 1995:3).

Starting in the early 1990s, major regional conflicts started to be replaced by small-scale contingencies (e.g., Somalia, Bosnia, Kosovo) and Human Relief Operations. The desired end-state for military actions throughout the 1990s was no longer characterized in terms of the incapacitation of the enemy's force nor in terms which US planners had much recent experience.

Senior US leaders recognized the need to transform its forces and doctrinal concepts to better meet the challenges of the "new world order." Joint Vision 2020 placed a strong emphasis on cooperation between the services, allies, and non-DoD government agencies to achieve "full-spectrum dominance" (Shelton, 2000:8). This document was a catalyst for many doctrinal, organizational, and training changes which improved our ability to conduct joint operations in the 21st century.

By the beginning of the 21st century, doctrinal, organizational, and training changes were crystallizing into a concept called Effects-Based Operations (EBO). One of the seminal papers on EBO is "Effects Based Operations: Change in the Nature of Warfare," by Lieutenant General David A. Deptula. In his paper, Deptula adopted Warden's approach of identifying the enemy as a system and expanded the idea of parallel warfare. In Deptula's mind, the object of parallel warfare is "…to achieve effective control over the set of systems relied on by an adversary for power and influence" (Deptula, 2001:6). He defined control as "…the ability to dominate an adversary's influence on strategic events" (Deptula, 2001:5).

Within this concept of control, Deptula departs from Warden's target-based approach. Instead, Deptula says an attacker can "…achieve certain effects against portions of a system that render the entire system ineffective [to] yield effective control over the system" (Deptula, 2001:5-6). By focusing on the effects needed to control a system rather than concentrating on the system's destruction, available forces can be used more efficiently to produce the desired end state.

1.1.2. Effects-Based Operations (EBO)

The current joint definition of EBO is *"[O]perations that are planned, executed, assessed, and adapted based on a holistic understanding of the operational environment in order to influence or change system behavior or capabilities using the integrated application of selected instruments of power to achieve directed policy aims."* (JFWC Pamphlet 7, 2004:2). The instruments of power, or resources, are used to take actions against specific nodes within the system with the hopes of producing desired effects. For the purposes of this study, an effect is defined as a "*…physical and/or behavioral state of a PMESII system that results from a military or non-military action or set of actions"* (JWFC Pamphlet 7, 2004:2).

EBO has three key components—planning, execution, and assessment—that are enabled by a Collaborative Information Environment (CIE) and Operational Net Assessment (ONA) (JWFC Pamphlet 7, 2004:9-10). The CIE facilitates unity of effort between different actors operating at strategic, operational, and tactical levels. The ONA provides a holistic understanding of a system within an operational environment by defining it in terms of its individual systems (see Figure 1-1).

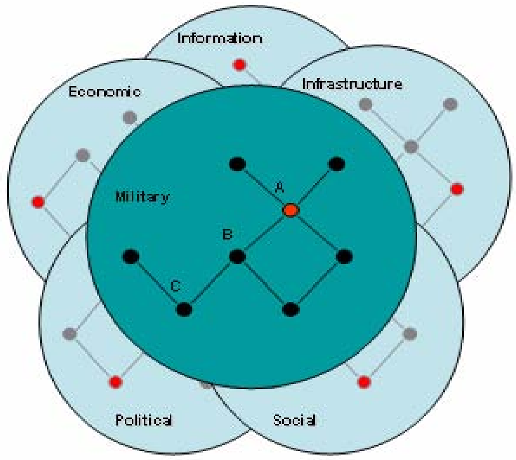

Figure 1-1. System of systems

Friendly, enemy, and neutral parties within an operation view the system of systems differently based on their objectives, perceptions of the operational environment, and the level at which they operate (strategic, operational, and/or tactical). Additionally, each actor attempts to influence the system using diplomatic, informational, military, and/or economic (DIME) actions.

In order to understand the implications of these two concepts, consider the following example. In Figure 1-2, a system is enclosed within a three-sided prism. Each face of the prism represents a strategic, operational, and tactical "lens" through which an observer views the system. The base of the prism represents all available DIME resources that form the foundation for coalition actions (the blue lines in Figure 1-2).

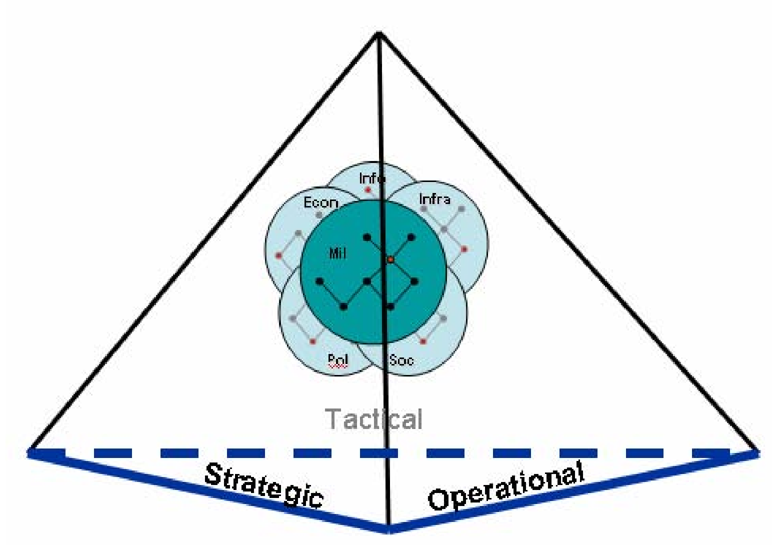

Figure 1-2. EBO Prism

The center of the sphere contains the true system, all actions, and other factors contained within the operational environment. Actors view the system, actions, and effects through the strategic, operational, or tactical “lenses.”

A commander’s objectives, access to information, and perception of the operational environment may bias his or her view of the system, actions taken against the system, and the effects generated by those actions. Commanders focus on the nodes within the system that are related to achieving their objectives. Access to information dictates a commander’s ability to correctly identify all the relevant nodes within a system or know all actions being applied to the system. Perception, on the other hand, impacts a commander’s understanding of how the nodes within a system are related. If a commander’s perception of the system clouds his or her understanding, it will also distort his or her view of effects.

Second, commanders look at the system differently through each lens. At the tactical level, for example, a squadron commander may view a surface-to-air missile (SAM) radar as a target that must be destroyed as tasked. However, he or she may also look through the operational lens to understand that by destroying the SAM radar, the air defenses in the southern region of the country will be disabled. In the former case, the single node (the SAM radar) represents the total system. In the latter case, the system is defined by the nodes constituting the southern air defenses.

Third, there is not necessarily a one-to-one mapping between effects and objectives or between effects and actions. A single action can produce multiple desired or undesired effects that may contribute to or hinder a commander's ability to achieve the desired end state. For example, attacks against Baghdad's transformer yards during Operation DESERT STORM shut off power in the city (desired effect), indirectly crippled the city's water and sewer systems (undesired effects), and severely impacted Baghdad's hospital operations (undesired effect) (Mann, 2002:25). Saddam Hussein did not repair the damage following the war and used the poor living conditions to hurt the image of the United States in the Arab world (Mann, 2002:25). In this case, the action (i.e., attacking the electrical power grids) caused undesired effects at operational and strategic levels in addition to achieving its desired effect.

1.1.2.1. Implementation Requirements

To conduct EBO, military commanders and planners must obtain a clearly defined end state from national leadership, translate the desired end state into fundamental campaign objectives, and clearly state desired effects in actionable terms to achieve the campaign's objectives. To facilitate this type of planning, a common terminology and taxonomy must exist between services to clearly translate fundamental objectives and desired effects across all echelons of command.

After the commander identifies what is important to achieve the end state, planners must identify the key adversary nodes that should be attacked using a coherent system of systems analysis. By looking through the operational and tactical lenses of the EBO prism, planners attempt to gain a holistic understanding of each node within the system of systems. Using this holistic understanding, planners are able to identify the set of enemy nodes against which all actions are focused.

Candidate actions must then be scrutinized to understand the desired and undesired effects they may generate. Once all actions and their effects are understood, a structured approach is required to determine the most appropriate portfolio of actions to produce the maximum number of desired effects while minimizing the number of undesired effects.

The portfolio of actions is defined, in part, by the resources that are available to the combatant commander. History provides countless examples of campaigns where commanders did not have sufficient resources to enable all the necessary actions to achieve victory. However, in many cases, victory was still obtained through a superior understanding of the best use of limited resources against an enemy. It is imperative for commanders and planners to understand the value of available resources within the context of the campaign objectives and desired end state.

1.1.2.2. Implementation Challenges

Effects-based planning can be difficult. It requires a cultural shift through changes in military doctrine, training and education. EBO requires intelligence, surveillance, and reconnaissance capabilities that can help commanders understand the operational environment as a complex system. It also requires us to redefine our combat assessment practices to quantifiably measure the "effects" of kinetic and non-kinetic actions alike.

First, within a military operation, a commander makes decisions with a multitude of considerations in mind. EBO asks the commander to identify which considerations are relevant, clearly communicate all of these considerations in the form of fundamental objectives (e.g., gain and maintain air supremacy throughout the campaign) and means objectives (e.g., neutralize enemy air defense systems to support the previous fundamental objective), and link the objectives to the desired end state produced by national leaders.

Second, course of action evaluation is more complex in an EBO framework. In contrast to target-based and objective-based approaches, EBO requires commanders to consider all direct and indirect effects produced by a given action. At first glance, one would appreciate the additional insight before choosing a particular action. However, in situations where there are hundreds or thousands of actions from which to choose, course of action evaluation becomes challenging.

Third, conflicting campaign objectives can make course of action selection more difficult within EBO due to increased appreciation of cascading effects. In target-based and objectives-based planning, course of action selection focused on the achievement of a specific objective. However, using EBO, commanders must also consider the impacts to other campaign objectives (e.g., destroying a nation's electrical grid to support military objectives could prolong the attainment of reconstruction objectives after hostilities have ceased).

Fourth, EBO shifts planning practices from focusing on kinetic actions with traditional military resources to considering a broad spectrum of kinetic and non-kinetic actions that are enabled by all instruments of power, some of which are not under the commander's control. This observation highlights an increased need for a commander to understand the value of a given resource within the context of campaign objectives.

1.2. Problem Statement

Military commanders need to understand the value of their available resources in the context of achieving a campaign's desired end state. At best, a resource's value is currently expressed in terms of its ability to perform specific actions against specific targets with little to no appreciation of cascading effects. While this limited view of a resource's value is sufficient when selecting the "best" action to take against a specific node, it does not state the resource's value within the context of the overall campaign.

The primary goal of this research is developing a method for calculating the value of a resource within the context of campaign objectives to provide additional insight to military commanders when making resource allocation decisions. A secondary goal of the research is creating a method to identify conflicting and competing objectives. A conflicting relationship occurs when the attainment of one objective is the direct cause of the degradation in the attainment of another objective. In contrast, competing objectives require the simultaneous use of the same resources when there are not enough resources to satisfy all objectives. By understanding a resource's value within the context of campaign objectives and understanding the relationships between objectives, commanders can make better resource allocation decisions.

1.3. Research Scope

This thesis uses the following approach. The methodology requires a graphical representation of a system of systems, a desired end state, and a commander's campaign objectives. The graphical representation is translated into a state model to reflect the physical, functional, and behavioral status of each node within the system of systems.

The baseline system state, desired end state, and campaign objectives are then expressed in terms of the state model to provide the necessary means for constructing a multiple objective value model. The multiple objective value model contains all of the commander's objectives and is used to calculate the value of each resource for a given operational plan.

Conflicting objectives are identified by using the state model and value model. For a given course of action, the value model is used to determine cases where the desired effect to achieve one objective causes a reduction in the attainment in another objective. The state model is then used to identify the relationships or key nodes within the system that cause the conflict.

Competing objectives are identified through the use of an integer program. An objective function, resource supply constraints, and additional constraints are developed to help planners identify the minimum number of resources that are required to achieve the maximum number of campaign objectives. Competing objectives are identified by analyzing binding resource constraints. If there is only one objective that is affected by the binding resource constraint, there is no feasible solution. However, competitive objectives are identified if there are multiple objectives that require the simultaneous use of the limited resources. If there are no binding constraints, there are no competing objectives and all campaign objectives are achieved.

1.4. Assumptions

The research within this thesis is based upon the following assumptions. First, all stated objectives are considered necessary to achieving the desired end state. Second, objectives may have different levels of importance to the attainment of the desired end state. Third, an objective is achieved by creating either a single desired effect or multiple desired effects. Fourth, it is possible for a single action to generate multiple effects (desired and undesired) at strategic, operational, and tactical levels. Fifth, the methodology is deterministic. A planned action is considered to have a 100% probability of succeeding if the appropriate resources are allocated to the accomplishment of that action. This assumption could be relaxed using utility theory. However, value theory is used for the purposes of this study. Sixth, the methodology only covers one planning horizon and is not dynamic. The assumptions and their potential impacts are discussed in greater detail in Chapter 3.

1.5. Thesis Organization

The structure of this thesis begins with a review of EBO terms and definitions, a review of the mathematical notation used to describe the system of systems, and a review of weighting techniques used when constructing a value model. Chapter 3 develops a methodology to perform effects-based planning. Chapter 4 contains a demonstration of the EBO methodology developed in Chapter 3. Chapter 5 presents conclusions from this analysis, highlighting key results, and presents recommendations for future research.

2. Literature Review

2.1. Introduction

This chapter is divided into five main sections. Section 2.2 captures the processes, essential terms, and definitions within an EBO framework as defined in current joint doctrine. Section 2.3 includes a comprehensive set of joint doctrinal terms and definitions required for System of Systems Analysis (SoSA). Section 2.4 describes McLamb's mathematical notation for characterizing a system as an operational network (McLamb, 2005:1). Section 2.5 summarizes McKenna's method for selecting weighting techniques for multiple attribute decision making applications (McKenna, 1997:1).

2.2. EBO Terms and Definitions

As mentioned in Chapter 1, the current joint definition of EBO is *"[O]perations that are planned, executed, assessed, and adapted based on a holistic understanding of the **operational environment** in order to influence or change **system** behavior or capabilities using the integrated application of selected **instruments of power** to achieve **directed policy aims**."* (JFWC Pamphlet 7, 2004:2)

There are four key terms within this definition—operational environment, system, instruments of power, and directed policy aims. The **operational environment** is *"…a composite of the elements, conditions, and influences that affect the employment of resources and capabilities and that bear on the decisions of the commander"* (JFWC Pamphlet 7, 2004:2). From a military planning perspective, allocation decisions are influenced by a myriad of considerations (e.g., weather, terrain type, distance to target, and rules of engagement). As another example, diplomatic and political considerations may influence a coalition commander's decision when approving a given course of action (e.g., coalition members, overflight rights).

The **system** is a *"…functionally, physically, and/or behaviorally related group of elements that interact together as a whole. To facilitate system-of-systems analysis, EBO currently considers that the operational environment is comprised of Political, Military, Economic, Social, Infrastructure, and Information (PMESII) systems"* (JFWC Pamphlet 7, 2004:2). The true system of systems is defined differently by different participants and/or non-participants within a given campaign based on their perceptions and available information. System definition may also differ between the strategic, operational, and tactical levels of war based on a participant's needs and objectives. For example, a participant at the strategic level may view an adversary's military as one aggregated node. At the operational level, a different participant may define the military system with a combination of aggregated nodes and individual nodes that are not explicitly captured in the strategic system view. At the tactical level, a single SAM launcher, its power supply, and communications links may constitute the entire military system for the purposes of planning an air strike. The concept of different system views is expanded in Chapter 3.

Instruments of power are "*…all ways and means—Diplomatic, Informational, Military, Economic (DIME) and others—available to the President to influence the operational environment*" (JFWC Pamphlet 7, 2004:3). Within a campaign context, a military commander may not have direct control over the diplomatic, informational, or economic instruments of power. While focused on military resources and capabilities within his control, the military commander must maintain an awareness of the remaining instruments of power and their impacts to the enemy system when used by the President and other agencies.

Directed policy aims are *"…the President's objectives that comprise the desired national end state relevant to the operation at hand"* (JFWC Pamphlet 7, 2004:3). Within the planning process, the combatant commander translates strategic national objectives into a set of operational campaign objectives. These objectives directly support the desired end state.

An **effect** is the *"…physical and/or behavioral state of a PMESII system that results from a military or non-military action or set of actions"* (JWFC Pamphlet 7, 2004:2). The current definition of effect is limited, ignoring the functional state of a system. In 2002, Air Combat Command (ACC) defined a functional effect as the ability to influence a target's ability to function properly (ACC, 2002:19). Accordingly, there should be a distinction between behavioral and functional states.

For example, an army division is modeled as a node within a system. The division's end strength is represented by the division's physical state. The behavioral state represents the division's morale or willingness to fight. The functional state represents the division's ability to fight. If the distinction between physical, functional, and behavioral states is not made within the definition of an effect, certain courses of action and the effects they produce may not be captured. Therefore, within this thesis, an effect is described as the physical, functional, and/or behavioral state of a system that results from a military or non-military action or set of actions.

There are many types of effects within an EBO framework. First-order effects, also known as **direct effects**, are "…*those [effects] that result immediately from the* *action…upon the target*" (Kreighbaum, 1998:51). For example, a first-order effect could be the physical destruction of a bridge.

Second-order effects, called **indirect effects**, are a result of the first-order event and may have "…some kind of a systemic influence" (Kreighbaum, 1998:51). For example, by destroying the bridge, the logistics supply line is cut to a forward area, decreasing an army division's ability to fight (second-order, indirect effect).

In 2002, ACC identified a special type of indirect effect, called a **cascading effect,** that "…ripple[s] through an adversary system, often affecting other systems" (ACC, 2002:32). For example, a special forces unit destroys an electrical substation (direct effect) in order to degrade an adversary's command and control network (indirect effect) to degrade air defense capabilities within the region (cascading effect). However, the destruction of the power grid also leads to the disruption of power within the city (indirect effect). Local hospital operations are disrupted (cascading effect), thereby causing the local population to become angry and frustrated (cascading effect).

Cumulative effects are the "…*aggregate result of many direct or indirect effects against an adversary*" (ACC, 2002:32). For example, many actions are taken to produce effects on individual SAM system elements, airfields, and command and control facilities. All of these actions are designed to produce the cumulative effect of neutralizing the adversary's integrated air defense system (IADS) to achieve air superiority in the region.

Strategic effects *"…contribute to reducing and unbalancing the enemy's overall political, military and economic capacities as well as psychological stability…"* and generally *"…require a longer time to manifest themselves than do effects at the* *operational and tactical levels…"* (Kreighbaum 2004:14-15). However, Kreighbaum's thesis focuses on force application operations in a wartime environment. In a truly holistic sense, this definition is very limited. Actions are not always designed to produce negative effects to an enemy system within a wartime environment. For example, the United States (US) often uses trade agreements and economic aid packages (economic instruments of power) to provide balance and improvement in a neutral nation's "economic capacity" in an effort to shape that nation's willingness to support US objectives. Therefore, it is more appropriate to define a **strategic effect** in terms of its ability to change the overall political, military, and economic capacities and psychological states of allies, neutral parties, and adversaries.

Operational effects *"…contribute to reducing and unbalancing the enemy's capacity to conduct successful campaigns and wage war" and "…usually take less time to be realized than do strategic ones*" (Krieghbaum, 2004:15). For example, gaining and maintaining air superiority is a common operational objective within a campaign. The cumulative effects that are produced to achieve air superiority are examples of operational effects. The definition is limited for the same reasons as mentioned in the previous paragraph. Therefore, **operational effects** are single or, most likely, cumulative changes to a system with indefinite durations.

Tactical effects *"…contribute to reducing and unbalancing the enemy's capacity to conduct battles on a relatively localized basis*" (Krieghbaum, 2004:15). In addition to assuming a wartime environment, the definition focuses solely on functional effects by specifically referencing an enemy's "capacity" to fight. Therefore, this thesis defines **tactical effects** as short duration changes to a system on a relatively localized basis.

2.3. System of Systems Analysis (SoSA) Definitions and Notation

System of System Analysis (SoSA) is a critical capability for EBO. This effort *"…produces a nodal analysis which, along with effects development, forms the basis for coupling nodes to effects, actions to nodes, and resources to establish E-N-A linkages"* (JWFC Pamphlet 7, 2004:11). There are four key terms within SoSA that require further definition.

A **node** is *"…a person, place, or physical thing that is a fundamental component of a system"* (JWFC Pamphlet 7, 2004:11). A node may represent an individual entity (e.g., a SAM launcher), a body of entities (e.g., a SAM complex), or an aggregation of nodes (e.g., a country's integrated air defense system).

A **link** is "*a relationship between nodes. Links can be behavioral, physical, or functional*" (JWFC Pamphlet 7, 2004:11). Links may be expressed in qualitative and quantitative terms and provide the means for assessing cascading and indirect effects.

Multiple effects may potentially occur throughout the system of systems as a result of a single action against a specific node due to its relationships with other nodes. Effects may describe the state of the individual node, an aggregation of nodes, or the entire enemy system.

An **action** is *"an activity directed at a specific node"* (JWFC Pamphlet 7, 2004:11). Unlike effects, actions are not classified as strategic, operational, or tactical. Actions are created through the employment of DIME resources.

A **resource** is *"…the forces, materiel, and other assets which can be employed to conduct an action"* (JWFC Pamphlet 7, 2004:11]. Within a strategic and operational EBO framework, resources are all DIME instruments of power that are at the disposal of national and international leaders for a given situation. The definition is sufficient for the purposes of this research.

Joint doctrine defines **objectives** as "*…the clearly defined, decisive, and attainable goals toward which every military operations should be directed*" (JWFC Pamphlet 7, 2004:11). While this definition is acceptable for traditional military planning, it is insufficient for the purposes of EBO and this thesis. EBO assumes that other government and non-government agencies operate to achieve a campaign's objectives. Therefore, the term "military operations" is limiting.

Second, in Chapter 2, the objectives hierarchy is translated into a state model to define an objective as the desired end state of a single node or aggregation of nodes. Therefore, in this study, **objectives** are the clearly defined, decisive, and attainable goals, *represented by the desired end state of a single node or aggregation of nodes*, toward which *all* operations should be directed.

2.4. Mathematical Notation to Describe an Enemy System

Assuming an enemy is already modeled as a system of systems, the first logical step is expressing the system in terms of its nodes, links, and states. This step allows analysts to compare the current system state with the desired end state to plan, execute, and assess the effects required to achieve the desired end state.

McLamb created a mathematical notation to describe an operational network in terms of its nodes and links (McLamb, 2005:1). The operational network ($\mathcal{A}$) is completely characterized by the set of all nodes ($\mathcal{N}$), the current state of all nodes ($\mathcal{C}$), the linkage between the nodes ($\mathcal{L}$), and the functions relating the states of the nodes ($\mathcal{F}$):

$$\mathcal{A} = \{\mathcal{N}, \mathcal{C}, \mathcal{L}, \mathcal{F}\}$$

Nodes are considered the smallest, decomposable entities within a system. For a system of k nodes, the set $\mathcal{N}$ is expressed as

$$\mathcal{N} = \{n_1, n_2, \ldots, n_k\}$$

Each node, n_i, is described in terms of its current state. Within an EBO framework, the state of a given node, N_i, is expressed in terms of its physical, functional, and/or behavioral status. McLamb uses the following notation to represent the state vector in terms of its physical, functional, or behavioral attributes

$$N_i = \left[N_i^P, N_i^F, N_i^B \right],$$

where N_i^P represents the physical state of n_i, N_i^F represents the functional state of n_i, and N_i^B represents the behavioral state of n_i (McLamb, 2005:2). Each attribute can be expressed in quantitative or qualitative states. In theory, the attributes could be expressed as discrete or continuous states. In practice, discrete states are used. For example,

$N_i^{(P)}$ = {"Fully Intact", "Partially Damaged", "Destroyed"}
$N_i^{(F)}$ = {2 missile launch capability, 1 missile launch capability, 0 launch capability}
$N_i^{(B)}$ = {"Friendly", "Neutral", "Belligerent"}

In this example, n_i's current state, N_i, could be in one of $3^3 = 27$ unique states. However, if one looks closely, there are actually fewer than 27 possible states due to state interdependencies. For example, if N_i^P is "Destroyed," it is highly unlikely that N_i^F would be "Fully Capable" or "Partially Capable." Similarly, N_i^B would most likely be "Neutral" to US interests since it is destroyed.

The current state of the operational network ($\mathcal{C}$), then, is described in terms of the current states of all k nodes

$$\mathcal{C} = \{N_1, N_2, \ldots, N_k\}$$

However, $\mathcal{N}$ and $\mathcal{C}$ are insufficient to describe the enemy. The physical, functional, and behavioral relationships between nodes must be defined in similar fashion.

McLamb uses l_{ij} to define the link between n_i and n_j. Within his notation, there are three types of linkages between nodes (see Figure 2-1). In the first case, no relationship exists between n_i and n_j and $l_{ij} = l_{ji} = 0$. The second type of relationship is the unknown linkage. In this case, a relationship is known to exist but cannot be expressed in quantitative or qualitative terms. In this case, l_{ij} = [?]. The last type of relationship is the directed linkage. In this case, an arrow is drawn from the independent node to the dependent node. In the case of Figure 2-1, n_i influences n_j with the linkage expressed as $l_{ij} = 1$. However, n_j does not influence n_i. Therefore, $l_{ji} = 0$.

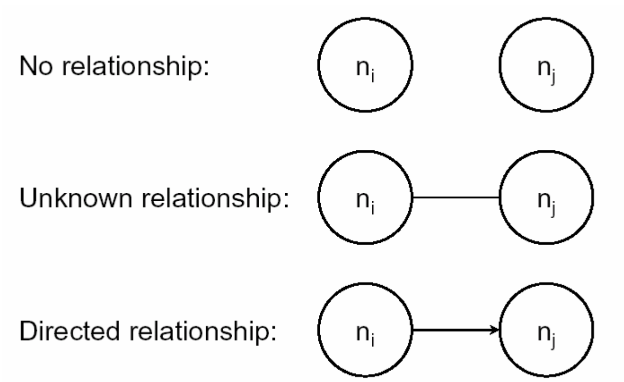

Figure 2-1. Types of linkages between nodes

$\mathcal{L}$, then, denotes the set of all existing linkages between k nodes of the existing network.

$$\mathcal{L} = \{l_{ij} : l_{ij} \neq 0, i, j \in [1, k], i \neq j\}$$

While l_{ij} expresses the linkage between n_i and n_j, L_{ij} states the functional mapping between states N_i and N_j. In the directed example from Figure 2-1, N_j is expressed as a function of N_i, or

$$N_j = L_{ij}(N_i)$$

where $L_{ij}(N_i)$ is expressed as

$$L_{ij}(N_i) = \begin{bmatrix} L_{ij}^1(N_i^1) \\ L_{ij}^2(N_i^2) \\ \vdots \\ L_{ij}^m(N_i^m) \end{bmatrix}$$

Furthermore, if n_j is dependent on multiple nodes (i.e., n_a, n_b, and n_i), its current state, N_j, is a function of N_a, N_b, N_c

$$N_j = f\,[L_{aj}(N_a), L_{bj}(N_b), L_{ij}(N_i)]$$

The functional mapping between nodes can be either quantitative or qualitative, depending on the availability of observable data. Using McLamb's example, a qualitative relationship could be expressed in terms of a positive or negative correlation between N_i and N_j (McLamb, 2005:5). If a favorable increase in N_i causes an increase with N_j, L_{ij} (N_i) = [+]. If a favorable increase in N_i causes a decrease in N_j, L_{ij} (N_i) = [-]. For an unknown linkage,

$$L_{ij}\,(N_i) = L_{ji}\,(N_j) = [?]$$

$\mathcal{F}$, then, can be described as the set of existing functional mappings between all nodes within the operational network

$$\mathcal{F} = \{L_{ij}, f_j : L_{ij} \neq 0, i, j \in [1, k], i \neq j\}$$

Collectively, $\mathcal{N}$, $\mathcal{C}$, $\mathcal{L}$, and $\mathcal{F}$ completely describe an operational network ($\mathcal{A}$). McLamb introduces the set $\mathcal{G}$ to describe the graphical representation of the network

$$\mathcal{G} = \{\mathcal{N}, \mathcal{L}\}$$

and introduces the set $\mathcal{S}$ to describe the state model

$$\mathcal{S} = \{\mathcal{C}, \mathcal{F}\}$$

Within this thesis, most of the discussion will focus on the state model ($\mathcal{S}$). However, the graphical network representation ($\mathcal{G}$) will also be used to augment discussions as needed.

While the system is completely characterized by $\mathcal{N}$, $\mathcal{C}$, $\mathcal{L}$, and $\mathcal{F}$, there is still something missing. Planners require the ability to aggregate individual nodes as they deem necessary. McLamb accounts for aggregation through the introduction of system notation (McLamb, 2005:8).

For example, a SAM system can be decomposed into a SAM commander (n_1), a SAM radar (n_2), and a SAM launcher (n_3). At the operational level, a planner may view the SAM system as a single node despite the fact that it can be further decomposed. At the operational level, the aggregated SAM system ($n_{[1]}$) is expressed as

$$n_{[1]} = \{n_1, n_2, n_3\}$$

The system notation can be extended to express the system in terms of its states ($N_{[1]}$), linkages $l_{[1]j}$, and functions [$L_{[i]j}$ (N_j)] in similar fashion.

2.5. Weighting Techniques

McKenna reviews 22 different weighting techniques used with Multiple Attribute Decision Making (MADM) theory and develops a method for selecting the most appropriate weighting technique for a given decision problem (McKenna: 1997:1). The weighting techniques are grouped into 7 different classes based on the availability of the decision maker (DM) and three factors (α,β, and γ). The three factors and their definitions are listed in Table 2-1 (McKenna, 1997:4).

Table 2-1. Weighting technique decision factors

Parameter	Symbol	Definition
α	AT	comparisons are done on the attributes
	AL	comparisons are done on the alternatives
	N	no comparisons are required
β	=	number of comparisons required is ≈ number of attributes (*n*) or ≈ number of alternatives (*m*)
	>	number of comparisons required is greater than *n* or *m*
γ	D	comparisons are direct equality or inequality judgments
	I	comparisons are indirect preference or indifference judgments

McKenna then classifies each weighting technique using the three factors and provides an excellent overview of each technique (McKenna, 1997:5).

Table 2-2. Weighting techniques

Technique	α	β	γ	Interpretation
Uniform Weights	N	NA	NA	NA
Unit Weighting	N	NA	NA	NA
Elicitation Measure	N	NA	NA	Information Content
Entropy	N	NA	NA	Information Content
Ordinal Ranking	AT	=	D	Importance
Categorization	AT	=	D	Importance
Successive Intervals	AT	=	D	Importance
Rating	AT	=	D	Importance
Point Allocations	AT	=	D	Importance
Ratio	AT	=	D	Importance
Swing	AT, AL	>	I	Importance
Pricing Out	AL	=, >	I	Scale Factor
Pair wise Comparisons	AT	>	D	Importance
Successive Comparisons	AT, AL	>	D	Importance
Half Sum Value	AT	=, >	D, I	Importance
Trade Off	AT	=, >	I	Scale Factor
Lotteries	AL	=, >	I	Scale Factor
Times Influential	AL	>	D	Importance
Neural Networks	N, AL	NA, >	NA, D, I	Importance
Subjective Probabilities	AL	>	I	Importance
Linear Regression	N, AL	NA, >	NA, D, I	Importance
Linear Programming	AL	=,>	D	Importance

Two decision tables are created to help an analyst determine the most appropriate decision table. The first decision table, called the "What the DM must do" selection tree, requires DM input to narrow down the number of possible weighting techniques. By asking a series of questions to the DM, the analyst is able to identify a smaller set of possible weighting techniques in addition to giving the DM an understanding of the level of commitment he or she is making to the decision problem (McKenna: 1997:51). The table numbers in Figure 2-2 correspond to McKenna's thesis, not the tables within this thesis.

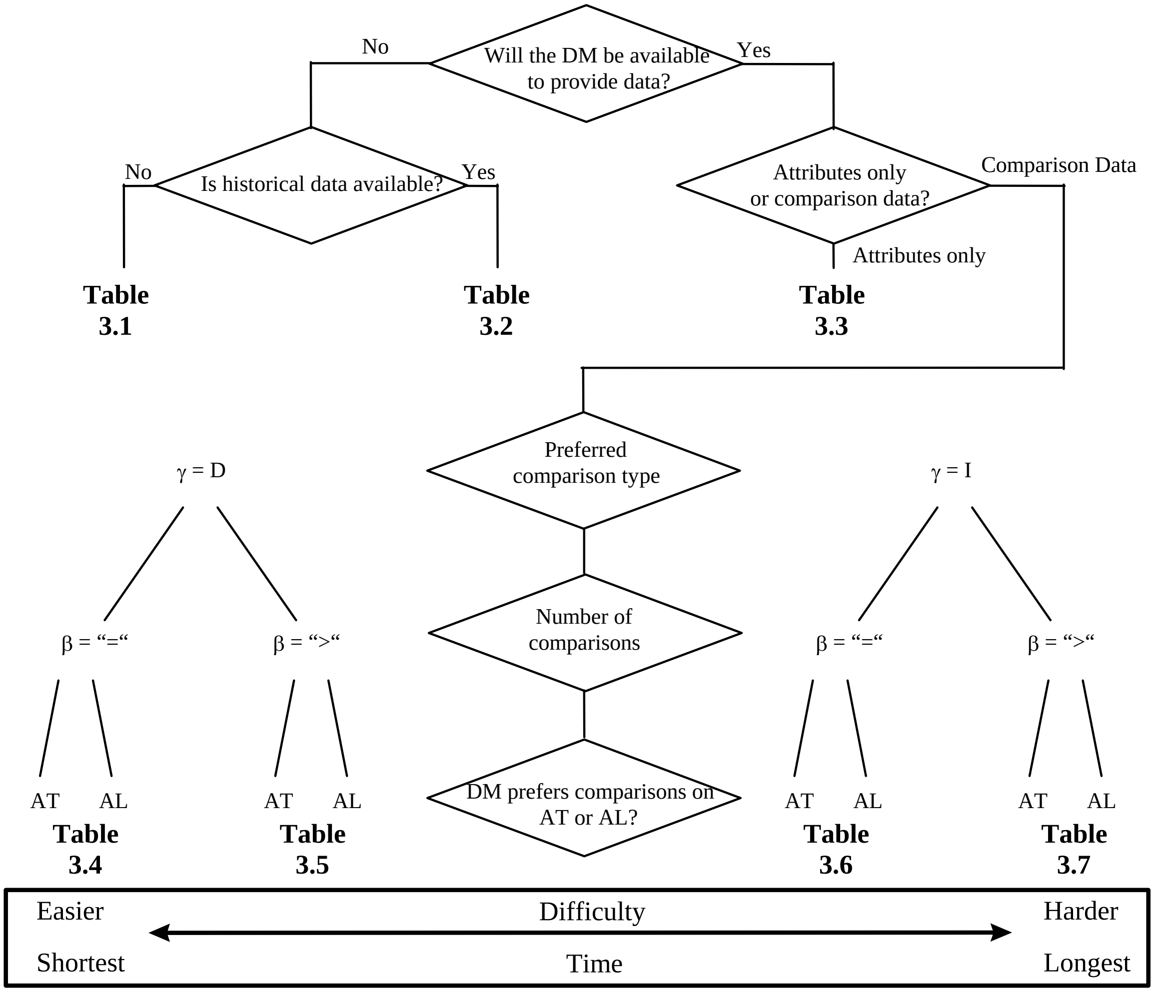

Figure 2-2. "What the DM must do" selection tree

The analyst uses a second decision tree, called the "Characteristics Required by the Analyst" selection tree, to further discriminate between the weighting techniques within the 7 classes based on the three questions in Figure 2-3 (McKenna, 1997: 52). The first question within the selection table is based on whether or not the analyst prefers to check if the weighting technique yields results that our consistent with the DM's gut feel. The second question addresses whether or not the weighting techniques is consistent with Multiple Attribute Value Theory (MAVT). The final question(s) is(are) used to determine how trustworthy a weighting technique is relative to other weighting techniques based on previous studies. After exercising both selection trees, the analyst selects the most appropriate weighting technique from the reduced set of possible options.

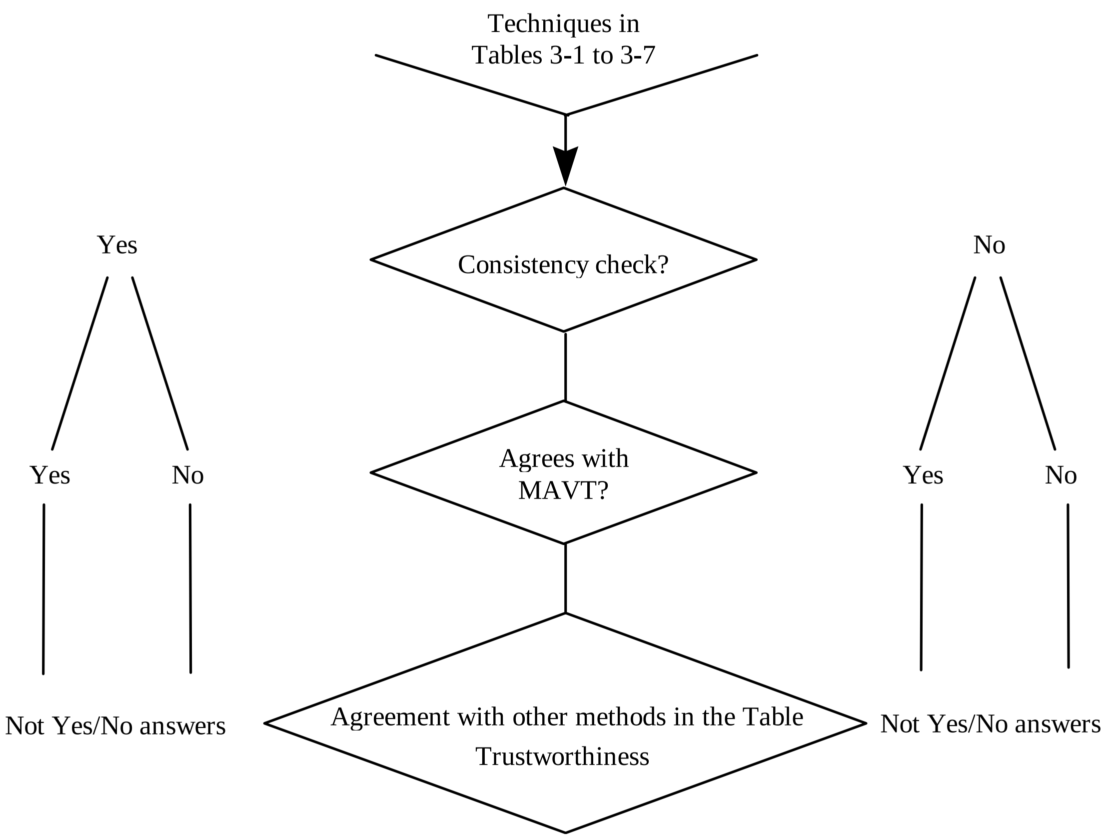

Figure 2-3. "Characteristics required by the analyst" selection tree

This selection method is a sound, methodical approach for selecting the most appropriate weighting technique for a given decision problem. The reader is encouraged to review McKenna's thesis for future decision problems.

3. Planning Methodology

3.1. Overview

This chapter describes the methodology required to determine the value of a limited resource within the context of competing objectives in addition to identifying the relationships between objectives. The chapter is divided into five sections. Section 3.2 describes the necessary starting conditions for applying the methodology along with stating the assumptions upon which the methodology was built. Section 3.3 describes the methodology used to build the state model that links objectives, effects, and nodes in a coherent fashion. Section 3.4 describes the value model that is crucial for quantifying a resource's value within the context of campaign objectives. Section 3.5 describes the method for using the state model to help identify conflicting objectives within a campaign. Section 3.6 describes the mixed integer program that is used for resource allocation and competitive objective identification.

As with any theoretical framework, the following algorithms and methods are not provided to give a commander or planner the "right" answer. At best, this framework will provide a planners or commanders with insight to help them make more informed resource allocation decisions. The framework's effectiveness will ultimately depend on the information at hand and the assumptions upon which the state model is constructed.

3.2. Starting Conditions and Assumptions

This thesis is not intended to capture all facets of operational planning and execution. It is focused on specific needs within the planning process—understanding the value of a resource to achieving campaign objectives and identifying the relationships between objectives. Therefore, it is necessary to provide relevant starting conditions and assumptions to determine the scope of the research.

3.2.1. Starting Conditions

Two elements are required to use this methodology. First, the enemy is already modeled as a system of systems in terms of nodes and links. At a minimum, the graphical depiction of the enemy system is required. Normally, J2 is assigned this responsibility for deliberate and crisis action planning situations. The model accommodates various levels of resolution. At a minimum, one node is required for each major component of the system (i.e., one node to represent the political system).

Second, national leadership and military commanders express a desired end state with associated strategic and operational objectives related in a hierarchical fashion. The methodology focuses on methods by which a commander can understand the value of a resource within the context of competing objectives, not on methods for translating a desired end state into an objectives hierarchy.

3.2.2. Assumptions

First, all stated objectives are considered necessary to achieving the desired end state. This assumption implies that the attainment of each objective has value and that the desired end state cannot be achieved by meeting a partial subset of the objectives.

Second, objectives may have different levels of importance to the attainment of the campaign's desired end state. For example, a commander states two objectives (i.e., "Gain and maintain air supremacy" and "Preserve power production and distribution within the country") that are necessary for achieving the desired end state. However, the commander views air supremacy as being more important to the attainment of the desired end state. The methodology incorporates weighting techniques to capture these preference statements regarding the importance of different objectives.

Third, an objective is achieved by creating either a single desired effect or multiple desired effects. This assumption requires the ability to express objectives in terms of system states, called **objective end states**. Objective end states are the preferred states for the key nodes within the system that correspond to the attainment of a given set of objectives. The assumption also requires a method to compare the current system state with an objective end state.

Fourth, it is possible for a single action to generate multiple effects (desired and undesired) at strategic, operational, and tactical levels. This assumption requires a method for capturing cascading effects within a system.

Fifth, for the purposes of this study, the methodology is deterministic. A planned action is considered to have a 100% probability of succeeding if the appropriate resources are allocated to the accomplishment of that action. This assumption highlights one of the main areas for potential follow-on research.

Sixth, the methodology only covers one planning horizon and is not dynamic. The first four assumptions are reasonable for a typical operational planning environment. However, the last two assumptions are necessary as a first step in developing a complete methodology. The relaxation of these assumptions should be the primary focus of any follow-on research regarding this model.

3.3. The State Model

The model is divided into two main parts. The first part begins with identifying the feasible state vectors for each system node and ends by determining the initial state of the entire system (A^0). The second part translates the campaign objectives in terms of objective end states, establishes the appropriate weights for objectives and their corresponding effects, and ends when the desired end state is expressed (A^*). The third part of the model links actions to nodes and resources to actions.

3.3.1. The Enemy as a System

Per the starting conditions, the intelligence function (J2) within a combatant commander's staff has already developed a graphical depiction of the enemy's system of systems. To complement the graphical depiction, two elements must be added—the possible state vectors for each node and the functions that capture the physical, functional, and behavioral relationships between nodes.

First, the possible state vectors for each node must be captured. From Chapter 2, a node's state (N_i) is expressed in terms of its physical, functional, and/or behavioral states (N_i^P, N_i^F, N_i^B). For the sake of symmetry within the model, every state vector (N_i) includes a physical value, functional value, and behavioral value. It is possible to have additional state attributes for a given node to capture relationships between a node and its neighboring nodes within a network.

A node is viewed as a fundamental component of a system. This statement implies that every node either serves some function within the system (e.g., a SAM radar detects aircraft), exhibits a behavior that can influence other nodes within the system (e.g., the temperament of the local civilians toward the coalition), or has both function and behavior (e.g., an infantry division).

For example, a tank only possesses physical and functional states. In this case, the tank's state vector only requires values for physical and functional states. The tank's behavioral state is nothing more than a placeholder and is expressed as “0” for a quantitative scale or “N/A” on a qualitative scale.

The possible physical, functional, and behavioral states are discrete values expressed quantitatively on an ordinal scale or qualitatively on a nominal scale. The number of discrete states for each attribute depends on the resolution of available assessment capabilities and the granularity required by a commander to make meaningful decisions. As the number of discrete cases for each attribute increases, the number of possible state vectors for a given node increases significantly.

For example, an analyst represents a single SAM radar as a node within a regional air defense system using 5 discrete physical states, 5 discrete functional states, and 1 behavioral state:

$$N_i^P = \{0, 0.25, 0.50, 0.75, 1\}$$
$$N_i^F = \{0, 0.25, 0.50, 0.75, 1\}$$
$$N_i^B = \{0\}$$

Using these possible states, there are (5)(5)(1) = 25 unique possible state vectors for a given node. For the sake of illustration, J2 says the available assessment capabilities do not support the level of detail for the physical and functional states. Therefore, the number of state values is reduced to 3 discrete physical states, 3 discrete functional state, and 1 behavioral state.

N_i^P = {“Destroyed”, “Partially Destroyed”, “Fully Intact”}
N_i^F = {“Not Functional”, “Partially Functional”, Fully Functional”}
N_i^B = {“N/A”}

Using each attribute's possible state descriptors, there are initially 9 unique state vectors describing the current state of the SAM radar.

Table 3-1. Possible SAM radar sites

Unique State Vector	Physical State	Functional State	Behavioral State
1	"Fully Intact"	"Fully Functional"	"N/A"
2	"Fully Intact"	"Partially Functional"	"N/A"
3	"Fully Intact"	"Not Functional"	"N/A"
4	"Partially Destroyed"	"Fully Functional"	"N/A"
5	"Partially Destroyed"	"Partially Functional"	"N/A"
6	"Partially Destroyed"	"Not Functional"	"N/A"
7	"Destroyed"	"Fully Functional"	"N/A"
8	"Destroyed"	"Partially Functional"	"N/A"
9	"Destroyed"	"Not Functional"	"N/A"

However, internal dependencies exist between the physical, functional, and behavioral states of a given node which may further reduce the number of possible state vectors. In the example, there are two state vectors in Table 3-1 with inconsistent physical and functional state values. If a SAM radar is assessed as "Destroyed," its functional state can only be "Not functional." However, the remaining state vectors are possible combinations of physical, functional, and behavioral states. Collectively, the remaining, feasible vectors form the set of possible state vectors for that given node.

After identifying the possible vector states for every node, the next step is developing the functions to capture the relationships between a given node and its surrounding nodes, or $L_{ij}(N_j)$, where $i \neq j$. This step is time intensive but crucial for modeling cascading effects throughout the system.

The second starting condition states that J2 already identified the nodes and links between them. Looking at the graphical representation of the network, the function development process starts by identifying the neighboring nodes upon which a node depends. In Figure 3-1, a SAM battery consists of an electrical power grid (n_1), a coarse acquisition radar (n_2), two fine acquisition radars (n_3 and n_4), and a SAM launcher (n_5).

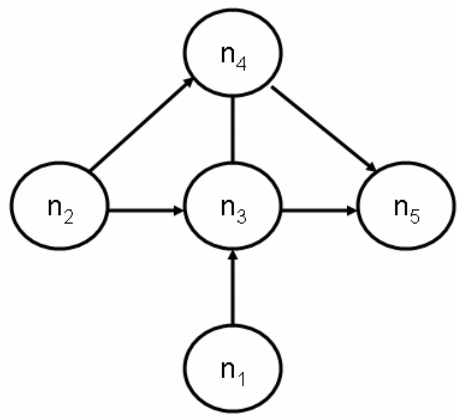

Figure 3-1. Example of a SAM battery

Nodes 1 and 2 are not dependent on the other nodes within the SAM battery. Their state vectors (N_1 and N_2) are only changed by actions taken against them. The remaining nodes (n_3, n_4, and n_5) are dependent on other nodes and require functions or rule sets to determine their current state vector.

The SAM launcher (n_5) does not have any physical or behavioral dependencies with respect to the other nodes. However, n_5's functional state depends upon the two fine acquisition radars (n_3 and n_4) for cueing information. Therefore, n_5's state vector, N_5, is expressed as

$$N_5 = \begin{bmatrix} N_5^P \\ N_5^F \\ N_5^B \end{bmatrix} = \begin{bmatrix} N_5^P \\ f(N_5^P, L_{53}(N_3), L_{54}(N_4)) \\ N_5^B \end{bmatrix}$$

Based on the previous paragraph, N_5^F only depends on N_5^P, N_3^F, and N_4^F. Ideally, a mathematical function can be constructed to calculate N_5^F using the three state values. However, in many cases, such a function may be difficult to obtain. In lieu of quantitative functions, other techniques are necessary to capture the relationships between nodes. As an example, this thesis uses IF-THEN-ELSE tables to identify N_5^F's value based on the other node states. Other techniques may be possible and will be discussed later in this chapter.

Table 3-2 is used to determine the value of N_5^F. It is assumed that the SAM launcher (n_5) cannot function if it is destroyed or if it cannot receive cueing information from the fine acquisition radars (n_3 and n_4). These assumptions are represented by 1 of 11 unique combinations that include "Destroyed" for N_5^P and/or "Not Functional" for both N_3^F and N_4^F. The remaining 16 combinations result in either a "Fully Functional" or "Partially Functional" state for N_5^F.

Table 3-2. Example IF-THEN-ELSE table

IF	**AND**		**THEN**
N_5^P	N_3^F	N_4^F	N_5^F
"Destroyed"	Any	Any	"Not Functional"
Any	"Not Functional"	"Not Functional"	"Not Functional"
"Fully Intact"	"Fully Functional"	Any	"Fully Functional"
"Fully Intact"	Any	"Fully Functional"	"Fully Functional"
ELSE			"Partially Functional"

There is one caution when using the IF-THEN-ELSE table approach. As stated earlier, the size of the IF-THEN-ELSE table is dependent on the number of "IF" nodes and the quantity of their possible physical, functional, and/or behavioral state values. For a node with many dependencies, the IF-THEN-ELSE table can quickly become unmanageable. There are two ways to keep the IF-THEN-ELSE tables to manageable sizes—aggregating nodes into systems and using the minimum number of discrete states to sufficiently express a node's state vector.

For example, the two fine acquisition radars (n_3 and n_4) are grouped into a single, aggregated node ($n_{[4]}$). In this case, N_5^F is now dependent on N_5^P and $N_{[4]}^F$. Assuming 3 possible states are used for $N_{[4]}^F$ ("Fully Functional," "Partially Functional," and "Not Functional"), the number of possible combinations in N_5^F's table is reduced from 27 to 9 (see Table 3-3).

Table 3-3. Modified IF-THEN-ELSE table

IF	AND	THEN
N_5^P	$N_{[4]}^F$	N_5^F
"Destroyed"	Any	"Not Functional"
Any	"Not Functional"	"Not Functional"
"Fully Intact"	"Fully Functional"	"Fully Functional"
ELSE		"Partially Functional"

Node aggregation may also allow an analyst to increase the level of granularity for a given "IF" node without increasing the size of the table. The fine acquisition radars were aggregated into a single node ($n_{[4]}$), reducing the table from 27 states to 9 states. If there is a need to express $N_{[4]}^F$ with increased granularity and a capability to obtain the necessary data, an analyst could use up to 9 unique state descriptors for $N_{[4]}^F$ without increasing the size of the original table (27 combinations).

When node aggregation is not possible, analysts should re-evaluate the number of discrete states they use to describe a node's physical, functional, and behavioral states. For example, a planner models the functional status of a country's Surface to Air (S-A) defenses using the functional states of the country's 7 SAM launchers (n_1 – n_7) and

4 anti-aircraft artillery (AAA) sites ($n_8 - n_{11}$). Initially, the planner specified each component's functional status as being either "Fully Functional," "Partially Functional," or "Not Functional."

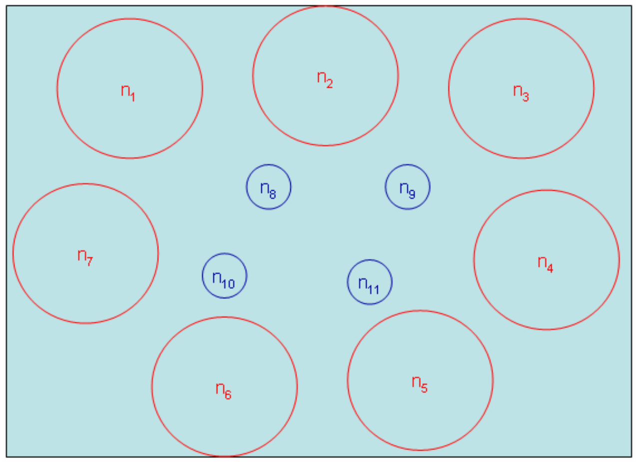

Figure 3-2. Notional S-A defense layout

At first glance, there are 3^{11} or 177,147 possible combinations to determine the functional status. To minimize the number of possible combinations, the country is divided into four regions (see Figure 3-3). The functional status of each region's S-A defenses is determined by using the functional status of each SAM launcher or AAA site whose threat ring overlaps the region.

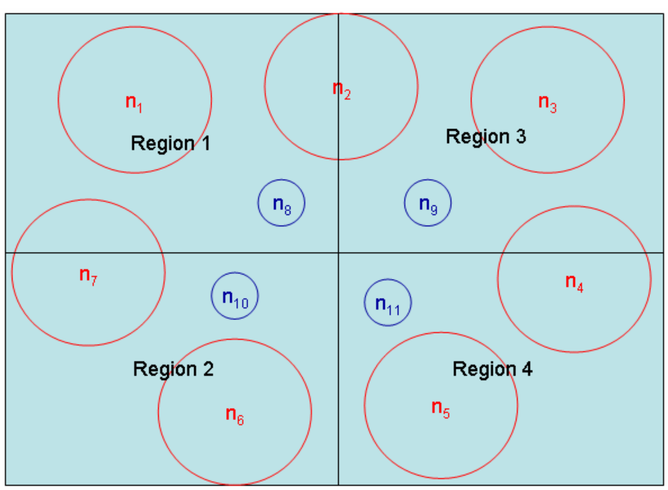

Figure 3-3. S-A Defense Regions

Table 3-4 summarizes the number of S-A defense nodes within each region and the resulting number of unique combinations to determine each region's functional state.

Table 3-4. Regional S-A defenses

Node	Region 1	Region 2	Region 3	Region 4
1	X			
2	X		X	
3			X	
4			X	X
5				X
6		X		
7	X	X		
8	X			
9			X	
10		X		
11				X
Combinations	**81**	**27**	**81**	**27**

To further reduce the number of possible combinations, SAM launchers and AAA sites are considered to be either "Fully Functional" or "Not Functional." This decision reduces the fidelity of the model but also reduces the number of possible combinations from 81 to 16 for Regions 1 and 3 and 27 to 9 for Regions 2 and 4. Since granularity and tractability of a model are directly proportional, planners need to carefully consider the number of discrete states used.

After all possible state vectors are known for each node and all relationships between all nodes are captured, the initial state of the enemy system, called A^0, can be expressed. Cascading effects resulting from a given action against a specific node can also be captured. Finally, the complete characterization of the enemy network allows an analyst to also express the desired end state (A^*), the campaign objectives that are necessary to achieve A^*, and the desired effects required to achieve the campaign objectives.

3.3.2. Desired End State and Campaign Objectives

Per the starting conditions, the desired end state and campaign objectives are already stated in qualitative terms. In order to measure the progress of the campaign, the desired end state and campaign objectives must be stated in terms of the state model.

The desired end state, stated by the President, identifies the end goals of the campaign. The combatant commander translates the President's strategic objectives into supporting operational military campaign objectives to achieve the desired end state. The EBO prism from Chapter 1 will be used to understand the relationship between the President's strategic objectives and the combatant commander's strategic and operational military campaign objectives.

For Operation IRAQI FREEDOM, President Bush set a political objective to "protect allies and supporters from Iraqi threats and attacks." (Moseley, 2003:4). Looking through the strategic lens in Figure 3-4, solely within the context of this single objective, President Bush may view Iraq's nuclear, biological, and chemical (NBC) weapons ($n_{[1]}$) and ballistic missile weapon systems ($n_{[2]}$) as aggregated nodes of the overall enemy system. Additionally, the Israeli government ($n_{[3]}$) and coalition partners ($n_{[4]}$) could be included as aggregated nodes due to President Bush's concern to protect allies.

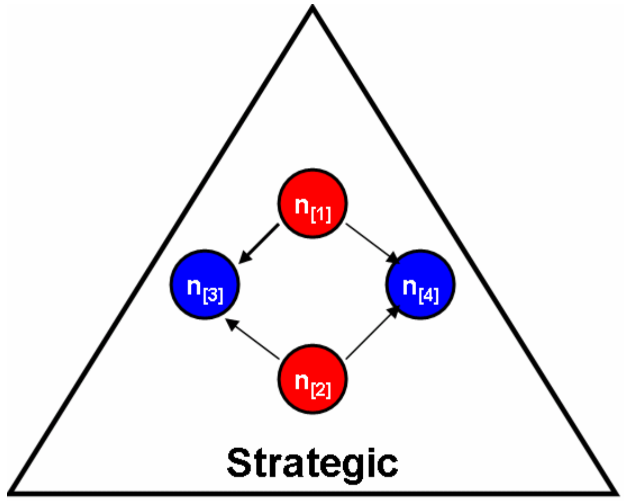

Figure 3-4. President's strategic view

The combatant commander translates the political objective into several supporting operational objectives. One of the combatant commander's operational objectives is gaining and maintaining air supremacy to enable air operations against NBC facilities and Iraqi scud launchers. Through the strategic lens, the combatant commander views President Bush's aggregated system. Through the operational lens, the combatant commander views President Bush's aggregated nodes, the Iraqi air defenses ($n_{[5]}$) and coalition air forces ($n_{[6]}$). Both views are captured in Figure 3-5.

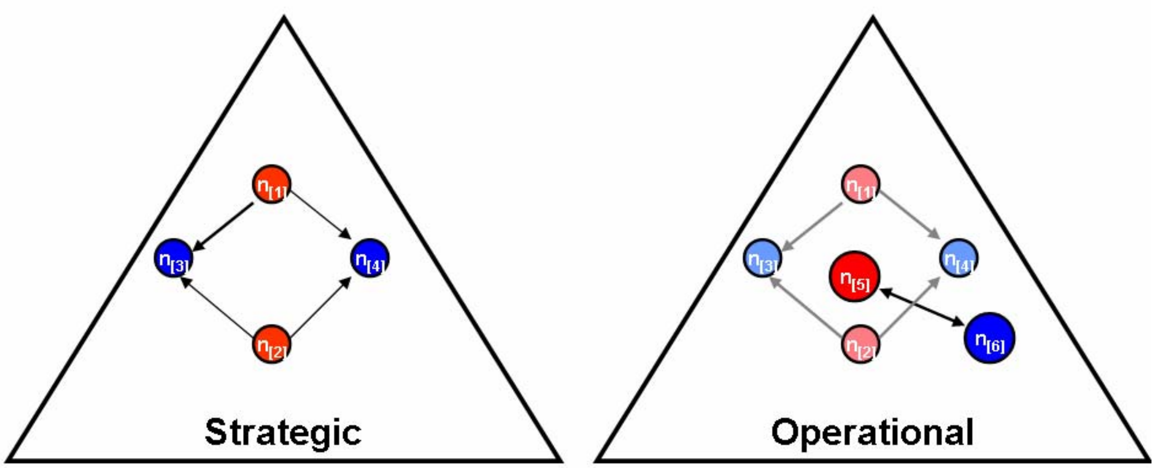

Figure 3-5. Combatant commander's strategic and operational view

The Joint Forces Air Component Commander (JFACC) shares a common understanding of the combatant commander's operational objective but views the Iraqi air defenses differently through his operational lens. Instead of viewing the air defenses as a single aggregated node (i.e., $n_{[5]}$ in Figure 3-5), the JFACC sees regional integrated air defense systems (IADS) as aggregated nodes ($n_{[7]}$ – $n_{[10]}$ in Figure 3-6).

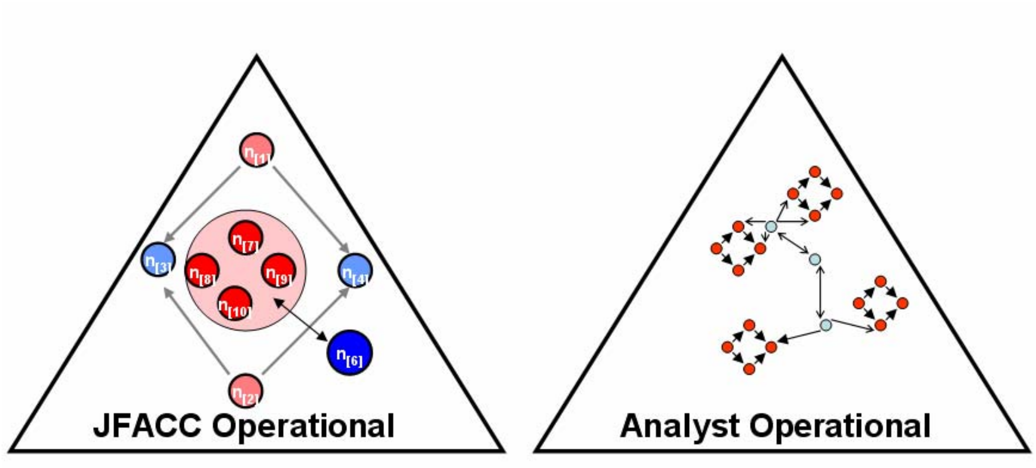

Figure 3-6. JFACC and analyst views

A planner on the JFACC staff, in turn, views each regional IADS through the operational and/or tactical lenses as a complex system of individual nodes that represent enemy aircraft, radars, power grids, SAM launchers, command and control facilities, and other physical entities (see Figure 3-6).

To measure the progress of the campaign, the different views in Figure 3-5 and Figure 3-6 can be expressed as an objectives hierarchy (see Figure 3-7). The combatant commander, JFACC, and planners view the enemy system consistently but at different tiers of the objectives hierarchy. The analyst views the hierarchy with additional lower level tiers not captured in Figure 3-7 since he or she is trying to plan specific actions to reach the objective's desired end state.

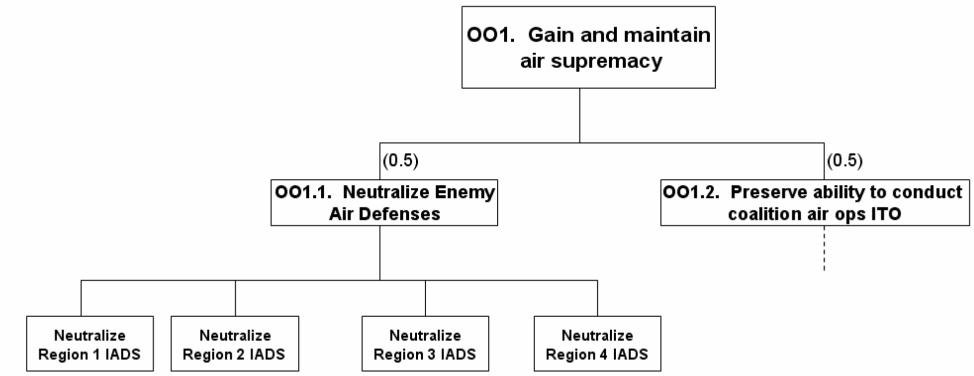

Figure 3-7. Operational objectives hierarchy

Figure 3-7 assumes that gaining and maintaining air supremacy, an operational objective, is attained by achieving two subobjectives ("Neutralize Enemy Air Defenses" and "Preserve ability to conduct coalition air operations ITO"). The first subobjective is a function of each regional IADS's operational state while the second subobjective is solely concerned with the status of coalition air forces. The subobjectives are considered independent of one another and considered equally important to gaining and maintaining air supremacy.

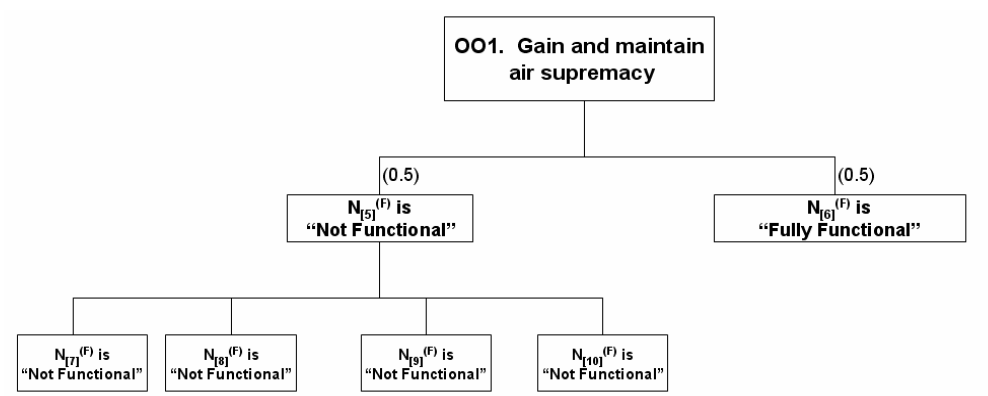

Figure 3-8. Objectives hierarchy expressed as objective end states

The desired end state, objectives, and subobjectives are modeled as aggregated or individual nodes of the system (see Figure 3-8). Table 3-5 contains the possible combinations needed to neutralize Iraq's IADS. It is assumed that if 3 of the 4 regional IADS are non-functional, then the country's IADS system is considered non-functional.

The functional state of each regional IADS is assessed as being not functional ("NF"), partially functional ("PF"), or fully functional ("FF").

Table 3-5. Several combinations of effects to attain OO1.1's objective end state

IF	AND			THEN
$N_{[7]}^{F}$	$N_{[8]}^{F}$	$N_{[9]}^{F}$	$N_{[10]}^{F}$	$N_{[5]}^{F}$
"NF"	"NF"	"NF"	Any	"NF"
"NF"	"NF"	Any	"NF"	"NF"
"NF"	Any	"NF"	"NF"	"NF"
Any	"NF"	"NF"	"NF"	"NF"

$N_{[5]}^{F}$'s IF-THEN-ELSE table could also be expressed at lower levels of aggregation. For example, planners decide that an IADS region is non-functional if two of the region's SAM launchers are disabled. Using Figure 3-3 to represent the 4 regional IADS, planners decide that the combinations in Table 3-6 will result in a non-functional IADS.

Table 3-6. Combinations of lower effects to attain OO1.1's objective end state

IF	AND						THEN
N_{1}^{F}	N_{2}^{F}	N_{3}^{F}	N_{4}^{F}	N_{5}^{F}	N_{6}^{F}	N_{7}^{F}	$N_{[5]}^{F}$
Any	"NF"	Any	"NF"	"NF"	Any	"NF"	"NF"
Any	"NF"	"NF"	Any	Any	"NF"	"NF"	"NF"

Actions are applied to individual nodes to produce desired effects. The effects at the individual node level may drive changes at the aggregated level. At the aggregated level, comparisons can be made between the new state of the system and an objective's desired end state. If the new state matches the desired end state for the given objective, the objective is achieved. If the objective is not achieved, then there is a planning disconnect from the desired system state and the objective.

Commanders are also interested in measuring progress toward obtaining a given objective. This can be done by mapping each node state to a specific value. Value functions for a node's physical, functional, and behavioral attributes are normalized from 0 to 1 to compare objectives on an equivalent scale. Value functions can be developed through commander elicitation or through quantitative arguments developed by planners.

Commander elicitation may not be possible due to his or her availability. In this case, a proxy decision maker can act on his or her behalf to establish values for each physical, functional, or behavioral state. Table 3-7 provides an example of values attained through commander elicitation.

Table 3-7. Mapping values to functional states

IF	**AND**			**THEN**	
$N^F_{[7]}$	$N^F_{[8]}$	$N^F_{[9]}$	$N^F_{[10]}$	$N^F_{[5]}$	**Value**
"NF"	"NF"	"NF"	Any	**"NF"**	**1**
"NF"	"NF"	Any	"NF"	**"NF"**	**1**
"NF"	Any	"NF"	"NF"	**"NF"**	**1**
Any	"NF"	"NF"	"NF"	**"NF"**	**1**
"FF"	"FF"	"FF"	"FF" or "PF"	**"FF"**	**0**
"FF"	"FF"	"FF" or "PF"	"FF"	**"FF"**	**0**
"FF"	"FF" or "PF"	"FF"	"FF"	**"FF"**	**0**
"FF" or "PF"	"FF"	"FF"	"FF"	**"FF"**	**0**
ELSE				**"PF"**	**0.4**

Quantitative arguments, on the other hand, can be developed at a planner's level. For example, suppose a planner is interested in assessing value for the IADS functional state represented in Figure 3-2. The planner could assess the value in terms of the percentage of the country protected by S-A defenses or the percentage of targets protected by S-A defenses. In this case, the value for $N^F_{[5]}$ is represented on a continuous scale from 0 to 1 despite having only 3 discrete states for $N^F_{[5]}$.

By describing the objectives and effects in terms of system nodes and their corresponding desired state vectors, the desired end state of the system (A^*) can be expressed in a coherent fashion. Additionally, by constructing objectives hierarchies with appropriate weights, the progress of the campaign can be measured.

3.4. Value Model and the Value of a Resource

The value of a resource is normally measured in terms of the resource's cost and performance characteristics or the resource's ability to accomplish a specific task (e.g., probability of success, severity of risk). In this thesis, the value of a resource is expressed *within the context of the degree of attainment of campaign objectives*. In order to express a resource's value in this manner, the following algorithm is used.

Step 1. Identify the objective end states for each objective

Step 2. Develop a single-dimensional value function for each end state

Step 3. Develop a multiple dimensional value function for each objective based on the single dimensional value functions in step 2

Step 4. Express objectives as sets of effects

Step 5. Determine value of each unit resource in terms of objectives (single and multiple objectives)

Table 3-8 is provided to help the reader understand variables and subscripts used within the model. The subscript notation is necessary to link resources to effects to objectives.

Table 3-8. Variable descriptions

Variable	Description
O_i	Objective *i*
E_{ij}	Effect *j* for Objective *i*
R_{ijk}	Resource Combination *k* used to produce Effect *j* for Objective *i*
R_a	Resource Type *a*
S_a	Slack variable *a* for Resource Type *a*

Two cases are explored within this section. First, the values of different resources are calculated for a single objective. In the second case, the values of the resources are calculated in terms of both campaign objectives to incorporate indirect and cascading effects.

3.4.1. Resource Value for a Single Objective

In the first step, objective end states are identified for each objective. As mentioned earlier in the chapter, objective end states are the preferred states for the key nodes within a system or subsystem that correspond to the attainment of a given objective. At a minimum, each objective is represented by at least one node (aggregated or individual) in its preferred physical, functional, and/or behavioral state.

In the second step, single-dimensional value functions are created for each physical, functional, or behavioral state that is used to model an objective end state. All of the single-dimensional value functions within the model are normalized between 0 and 1 to put the value of all objective end states on a common scale. Based on the existing operational plan, the degree to which O_1 (Gain and Maintain Air Supremacy) is attained depends on the functional states of Region 1 ($N^F_{[7]}$), Region 2 ($N^F_{[8]}$), and Region 3 ($N^F_{[9]}$). Each region uses the same value model for the purposes of this example.

There are three possible functional states for a given region i ($N^F_{[i]}$).

$$N^F_{[i]} = \begin{cases} 1 & \text{if} \quad \text{"Not Functional"} \\ 2 & \text{if} \quad \text{"Partially Functional"} \\ 3 & \text{if} \quad \text{"Fully Functional"} \end{cases}$$

The objective end state, $N^F_{[i]}$ = 1, is the most preferred functional state for a given region and is assessed a value of 1. In contrast, $N^F_{[i]}$ = 3, is the least preferred functional state for a given region and is assessed a value of 0. Commander elicitation yields a value of 0.25 for a “Partially Functional” state ($N^F_{[i]}$ = 2).

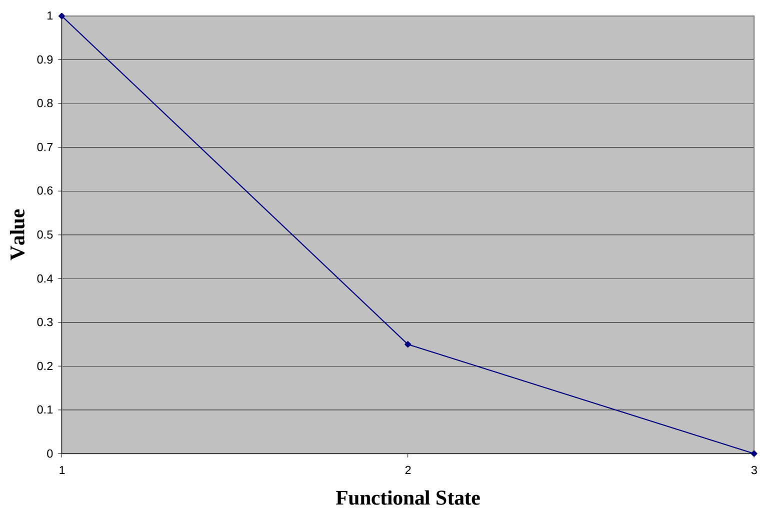

Figure 3-9. Value function for regional IADS's functional state

A single-dimensional, piecewise linear value function is built with this information (see Figure 3-9) since there are only three discrete states. If a state function possesses a large number of possible states (continuous or discrete), exponential value functions are recommended. The value function is then used to express the value of a given effect for a given objective.

For example, E_{11} is an effect that describes the transition of Region 1's IADS from a fully functional state to a non-functional state by neutralizing two SAM launchers (n_1 and n_2 in Figure 3-3).

$$E_{11} \equiv \Delta N_{[7]}^{F} = N_{[7]}^{F^0} \rightarrow N_{[7]}^{F^*}$$

The value of this effect is

$$V_1(E_{11}) = V_{1[7]}(\Delta N_{[7]}^{F}) = V_{1[7]}(N_{[7]}^{F} = 3) - V_{1[7]}(N_{[7]}^{F} = 1) = 1 - 0 = 1$$

In other cases, multiple effects drive a node to its preferred end state. For example, Region 3's functional state is reduced to a non-functional state through two different effects (E_{13} and E_{15}). Recall that E_{15} captures the indirect effect within Region 3 following the action taken against n_2 to produce E_{11}. E_{13} captures the effect produced after neutralizing a third SAM launcher (n_3). To avoid double counting, E_{15} captures the transition from a fully functional state to a partially functional state.

$$E_{15} \equiv \Delta N_{[9]}^{F} = N_{[9]}^{F^0} \rightarrow N_{[9]}^{F'}$$

The value of E_{15} is

$$V_{1[9]}(E_{15}) = V_{1[9]}(\Delta N_{[9]}^{F}) = V_{1[9]}(N_{[9]}^{F} = 2) - V_{1[9]}(N_{[9]}^{F} = 1) = 0.25 - 0 = 0.25$$

E_{13}, on the other hand, is calculated using the transition from the partially functional state to a non-functional state.

$$E_{13} \equiv \Delta N_{[9]}^{F} = N_{[9]}^{F^0} \rightarrow N_{[9]}^{F^*}$$

In this case,

$$V_{1[9]}(E_{11}) = V_{1[9]}(\Delta N_{[9]}^{F}) = V_{1[9]}(N_{[9]}^{F} = 3) - V_{1[9]}(N_{[9]}^{F} = 2) = 1 - 0.25 = 0.75$$

Collectively, both actions yield a value of 1, which is the same value of Region 3's S-A defenses at a non-functional state. Step 2 is not complete until there is a value function for each objective end state.

The third step combines the single dimensional value functions from Step 2 to create the multiple dimensional value function for each objective. In this thesis, it is assumed that an additive value function can be used. The general form of a multiple dimensional, additive value function is

$$V(x_1,\ldots,x_n)=\sum_{i=1}^{n} w_i \cdot V_i(x_i)$$

This form can be modified to state an objective's value function in terms of changes in the node states that represent the objective end states.

$$V(\Delta N_{[1]}^F,\Delta N_{[2]}^F,\ldots,\Delta N_{[n]}^F)=\sum_{i=1}^{n} w_{[i]} \cdot V_{[i]}(\Delta N_{[i]}^F)$$

This value function is constructed with only functional states. Physical states, behavioral states, and other states that are defined by a planner can also be used.

In the air supremacy example, the objective is represented by the functional states of the enemy IADS in Regions 1, 2, and 3. The corresponding additive value function is expressed as

$$V(O_1)=V_{[5]}(\Delta N_{[5]}^F)$$

or, at the next lowest level of aggregation,

$$V(O_1)=V(\Delta N_{[7]}^F,\Delta N_{[8]}^F,\Delta N_{[9]}^F)=w_{1[7]} \cdot V_{[7]}(\Delta N_{[7]}^F)+w_{1[8]} \cdot V_{[8]}(\Delta N_{[8]}^F)+w_{1[9]} \cdot V_{[9]}(\Delta N_{[9]}^F)$$

However, any change of a node's state within the SoSA model is also known as an effect. Therefore, the additive value function is also expressed as

$$V(E_{11},E_{12},E_{13},E_{15}) = w_{1[7]} \cdot V_{[7]}(E_{11}) + w_{1[8]} \cdot V_{[8]}(E_{12}) + w_{1[9]} \cdot [V_{[9]}(E_{13}) + V_{[9]}(E_{15})]$$

In this form, it is possible to calculate the value of an effect or set of effects in terms of the objective end states.

Additive value functions are built on an assumption of independence between attributes within a decision tree. For any complex adaptive system, including the model of an enemy system, independence cannot be guaranteed is not likely to be true. If independence assumptions are not true and an additive value function is used, the value of the different alternatives (i.e., resources) will either be “double counted” or, in the case of undesired effects with negative values, undervalued. In either case, multiplicative value functions are more appropriate due to their ability to account for the dependencies throughout the system.

The objective’s value function is a combination of the single-dimensional value functions from step 3 and weights, $w_{i[-]}$. The weights, $w_{i[-]}$, quantify a node end state’s relative degree of importance to the attainment of objective i. There are a variety of techniques that can be used to determine the weights for a given value function (see Table 2-2). For a majority of existing weighting techniques, the sum of the weights for the effects used to attain O_i sum to 1.

$$\sum_{\forall i | n_i \in O_1} w_{1[i]} = 1$$

In this example, uniform weighting is used. According to the existing operational plan, O_1 is achieved when three of the S-A defense regions ($n_{[7]}$, $n_{[8]}$, $n_{[9]}$ in this case) are driven to non-functional states. Each region is viewed as being equally important to the attainment of the objective.

$$w_{1[7]} = w_{1[8]} = w_{1[9]} = 1/3$$

$$w_{1[7]} + w_{1[8]} + w_{1[9]} = 1$$

Elicitation is a popular method used to capture an expert's assessment of the relative importance of each objective. For example, a planner states that Region 1's S-A defenses should be weighted 50% since half of the critical military command and control nodes are in Region 1. Regions 2 and 3 are considered half as important as Region 1. Based on this assessment, the weights are

$$w_{1[7]} = 0.50,\ w_{1[8]} = 0.25,\ w_{1[9]} = 0.25$$

Elicitation requires that an expert is available and is willing to devote the time to make weighting assessments and ensure consistency with the weighting results. The selection of weighting techniques should be handled with great care using the method described in Section 2.5. Once the weights are obtained, an objective's value function is complete. The process within this step can be re-accomplished to develop one value function that includes all campaign objectives and the weights that capture the relative importance of each objective to the overall campaign.

After the objective end states are identified for each objective, the next step is identifying the effects that are necessary to attain the objectives. Step 4 starts by assessing the initial status of the system using available information and the state model. Once this action is complete, the planner can then determine the number of state changes, or effects (E_{ij}), that are necessary to match the objective end states.

The air superiority example is used to illustrate this step. According to current assessments, the enemy's IADS and coalition air forces are both assessed as fully functional, or $\{ N^F_{[5]}, N^F_{[6]} \} = \{3, 3\}$. Based on this information, only one effect is necessary to attain the objective end state (coalition air forces are already in a fully functional state).

$$O_1 = \{E_{11}\}, \text{ where}$$

$$E_{11} \equiv \Delta N_{[7]}^{F} = N_{[7]}^{F^0} \rightarrow N_{[7]}^{F*}$$

The selection of objective end states is critical to the development of the effects that are needed to attain a given objective. For example, "Gain and Maintain Air Supremacy" is defined in terms of the enemy's IADS, which is decomposed into four different regional IADS in Figure 3-8. According to Table 3-5, O_1 is achieved when three of the four regional IADS are not functional. Assuming all the regional IADS are fully functional, O_1 is expressed as

$$O_1 = \{E_{11}, E_{12}, E_{13}\}, \{E_{11}, E_{12}, E_{14}\}, \{E_{11}, E_{13}, E_{14}\}, \text{ or } \{E_{12}, E_{13}, E_{14}\}$$

where

$$\begin{aligned} E_{11} &\equiv \Delta N_{[7]}^{F} = N_{[7]}^{F^0} \rightarrow N_{[7]}^{F*} \\ E_{12} &\equiv \Delta N_{[8]}^{F} = N_{[8]}^{F^0} \rightarrow N_{[8]}^{F*} \\ E_{13} &\equiv \Delta N_{[9]}^{F} = N_{[9]}^{F^0} \rightarrow N_{[9]}^{F*} \\ E_{14} &\equiv \Delta N_{[10]}^{F} = N_{[10]}^{F^0} \rightarrow N_{[10]}^{F*} \end{aligned}$$

Both methods are equivalent expressions of O_1's attainment. However, the second method makes step 3 more challenging. Therefore, careful considerations must be made when selecting objective end states.

Resource package selection is also important when determining the set of effects that affect the degree to which an objective is achieved. Each resource package, called labeled R_{ijk}, is linked to a desired effect (E_{ij}) and possibly other additional effects (e.g., indirect effects, cascading effects) that affect the attainment of O_i or other objectives.

R_{ijk}, represents a resource package k used to enable effect E_{ij} for objective O_i. It is assumed that, by selecting resource package R_{ijk}, effect E_{ij} occurs with certainty.

Put another way, R_{ijk} represents the resources a planner wishes to include to produce a given effect. For example, R_{ijk} can represent a single type of resource (e.g., 2 B-2 bombers) or a group of different types of resources (e.g., a strike package consisting of 4 F-16s, 4 F-15s, and 2 EA-6Bs). It can also represent munitions, enabling resources, or other resource types required by the planner (e.g., 2 B-2 bombers armed with 10 JDAMs enabled by GPS).

The resource type and quantities of resources within a given R_{ijk} depend solely on the actions taken to produce E_{ij}. For example, in order to produce E_{11} in the S-A defenses example, military planners develop three unique courses of action to drive Region 1's S-A defenses to a non-functional state. Table 3-9 includes three possible resource packages to produce $E_{11.}$

Table 3-9. Resource package to achieve E_{11}

Package	F-15	F-16	EA-6B	Info Ops	SOF
R_{111}	8	8	4		
R_{112}				1	
R_{113}					2

R_{111} represents two traditional strike packages to destroy two of the SAM launchers, n_1 and n_2, as depicted in Figure 3-3. R_{112} represents an information operations attack to the region's electrical grid. In this case, the enemy's electrical grid is monitored and controlled by a Supervisory Control and Data Acquisition (SCADA) system. The information operations team states that they can gain remote control of the SCADA system to disable all electrical power flowing to the region's air defense radars within that region. R_{113} uses two special operations teams to disable n_1 and n_2.

In the example, all resource packages are assumed to produce E_{11}. However, actions facilitated by R_{111} may also cause collateral damage to surrounding nodes near the SAM launchers. The actions in R_{112} may also allow coalition forces to control the electrical power distribution to other nodes within the region or inadvertently disable power to other nodes of interest (i.e., the Baghdad transformer yard example in Section 1.1.2). If a planner is interested in determining a resource's full value in terms of the overall campaign, cascading effects should also be linked to the appropriate resource package.

$$R_{111} \rightarrow \{E_{11}, E_{15}\}$$

$$R_{112} \rightarrow \{E_{11}, E_{22}, E_{31}\}$$

$$R_{113} \rightarrow \{E_{11}\}$$

For example, R_{111} produces E_{11}. By destroying n_2, R_{111} also drives the functional state of Region 3's S-A defenses to a partially functional state (E_{15}). If R_{111} is selected, there are impacts to the definition of E_{13}. E_{13} can no longer be expressed as Region 3's S-A transition from a fully functional state to a non-functional state. Otherwise, the value of taking a single action (destroying n_2) would be counted twice. In this case, E_{13} is redefined as a transition from a partially functional state to a non-functional state. This resource package selection culminates in a new set of effects required for O_1's attainment

$$O_1 = \{E_{11}, E_{12}, E_{13}, E_{15}\}$$

The previous paragraphs highlight the difference between traditional strategy to task development and effects-based planning. In the former case, the planner does not consider or model cascading effects, only valuing the contributions of the desired effect toward a single objective. In the latter case, planners include direct effects and indirect effects within the model. The mathematical model supports both planning philosophies.

If the planner is only interested in the value of a resource with respect to an individual objective, the process is quite simple. For example, the commander wishes to know the worth of different resources to the attainment of O_1. Based on the given plan, the following resource packages are used to achieve O_1. The data within Table 3-10 is notional.

Table 3-10. Effects and resources required to achieve O_1

Effect	Resource Package	F-15	F-16	EA-6B	Info Ops	SOF
E_{11}	R_{11}	8	8	4	0	0
E_{12}	R_{12}	0	0	0	1	0
E_{13}	R_{13}	0	0	0	0	1
E_{15}	R_{11}	X	X	X	0	0

E_{11} and E_{15} are produced by the same resource package. Therefore, the F-15, F-16, and EA-6B quantities are all "X" for E_{15} to avoid double counting the number of F-15s, F-16s, and EA-6Bs. Also, E_{11} and E_{15} collectively affect $N_{[9]}^{(F)}$. The form of the single objective value function in terms of the effects is

$$V(E_{11},E_{12},E_{13},E_{15}) = w_{1[7]} \cdot V_{[7]}(E_{11}) + w_{1[8]} \cdot V_{[8]}(E_{12}) + w_{1[9]} \cdot [V_{[9]}(E_{13}) + V_{[9]}(E_{15})]$$

Using uniform weighting and the single dimensional value functions, the values of each effect and the weights for each objective end state are calculated (results in Table 3-11).

Table 3-11. Value of each effect

Effect	$w_{i[-]}$	$V_{[-]}(E_{1j})$
E_{11}	0.33	1
E_{12}	0.33	1
E_{13}	0.33	.75
E_{15}	0.33	.25

To calculate the value of each resource type, each $V(E_{1j})$ is divided by the number of resource types used to produce E_{1j}. This calculation assumes that each resource type is equally important to producing the effect. Other schemes could be used to distribute an effect's value among the different resource types.

Table 3-12. Value of each resource type per effect

Effect	$w_{1[i]}$	$V_{[i]}(E_{ij})$	$V_{[i]}$(F-15)	$V_{[i]}$(F-16)	$V_{[i]}$(EA-6B)	$V_{[i]}$(Info Ops)	$V_{[i]}$(SOF)
E_{11}	0.33	1	0.33	0.33	0.34	0	0
E_{12}	0.33	1	0	0	0	1.00	0
E_{13}	0.33	0.75	0	0	0	0	0.75
E_{15}	0.33	0.25	0.08	0.08	0.09	0	0

The value of each resource type is then calculated with respect to O_1.

$$V(\text{all F-15s}) = \sum_{\forall i} w_{1[i]} \cdot V_{[i]}(\text{F-15s})$$
$$V(\text{all F-15s}) = w_{1[7]} \cdot V_{[7]}(\text{F-15s}) + w_{1[8]} \cdot V_{[8]}(\text{F-15s}) + w_{1[9]} \cdot V_{[9]}(\text{F-15s})$$
$$V(\text{all F-15s}) = (0.33)\cdot(0.33) + (0.33)\cdot(0) + 0.33\cdot[(0) + (0.08)]$$
$$V(\text{all F-15s}) = 0.14$$

This value represents the total contribution of all 8 F-15s to achieving O_1. To obtain the contribution of an individual F-15 to achieving O_1, simply divide V_1(F-15s) by the number of F-15s used to achieve the objective. Completing the calculations for the other resources, the value of each resource by type and individual unit for achieving O_1 is

Table 3-13. Value of a resource for a single objective

Resource Type	F-15s	F-16s	EA-6Bs	Info Ops	SOF Forces
Value (Type)	0.14	0.14	0.15	0.33	0.25
Value (Unit)	0.02	0.02	0.04	0.33	0.25

The reader is encouraged to focus on the relative differences between the different resource values, not the specific numbers. For example, based on the results provided in Table 3-13, the contributions of one information operations teams are much more significant than the contributions of a single F-15. This makes sense due to the fact that only one information operations team was required to drive a region's S-A defenses to a non-functional state.

As a reminder, the resource packages were developed using notional data to better explain the process. Arguments can be made as to whether or not the information operations team is actually 16.5 times more important than a single F-15. However, there can be no argument that the information operations team's contributions are much greater than the F-15 to achieve this objective for this operational plan.

Once the resource values are known, planners can group the resources into prioritized categories. The category ranges depend on the commander's preference or a planner's intuition. In the example, the value of each resource was calculated. Looking at the individual resource values in Table 3-13, there appears to be two major categories. Information operations teams and SOF teams are considered Priority 1 resources. The remaining resources, F-15s, F-16s, and EA-6Bs, are considered Priority 2 resources.

Table 3-14. Prioritized resource categories

Category	Resource	Value
1	Info Ops	0.33
	SOF	0.25
2	EA-6B	0.04
	F-15	0.02
	F-16	0.02

However, this prioritization method should only be used for an existing operational plan that has identified specific courses of action. First, resource values in this example are based on the specific courses of action and corresponding effects that are identified within the existing operational plan. If the courses of action within the operational plan change, resource value and prioritization will most likely change as well.

3.4.2. Resource Value for Multiple Objectives

Knowing the value of a resource for a single objective is useful. However, if a planner is interested in capturing cascading effects throughout the system, resource value should be stated in terms of all the objectives. In this example, three objectives are used to evaluate the previous example's set of actions (i.e., the actions enabled by the selected resource packages) and the value of the resources.

The first objective, O_1, is "Gain and Maintain Air Supremacy within the Theater of Operations" as was previously defined in the single objective example. The second objective, O_2, is "Preserve utilities within the theater of operations" and is primarily concerned with the functional state of the country's electrical power production and distribution system within the theater of operations, or $N_{[11]}^{F}$. The third objective, O_3, is "Preserve public health care services within the theater of operations." This objective is focused on the functional state of hospital services with the country, or $N_{[16]}^{F}$.

For O_2 and O_3, the country is divided into the same four regions that are used for O_1. For the purposes of this example, the following state representations are used for O_2 and O_3.

Table 3-15. Objective end states for O_2 and O_3

Objective	State Representations		
	Region 1	Region 2	Region 3
O_2	$N^F_{[12]}$	$N^F_{[13]}$	$N^F_{[14]}$
O_3	$N^F_{[17]}$	$N^F_{[18]}$	$N^F_{[19]}$

There are four possible states to address the functional state of a region's power system (4, 3, 2, 1) corresponding to the number of major cities in the region that have power services. A rating of 4 is the most preferred state, resulting in a value of "1." A rating of "1" represents 1 or no major cities having power services. This is the least preferred rating and is assessed a value of 0. A rating of "2" yields a value of 0.35 and a rating of "3" results in a value of 0.8. The resulting value function is captured in Figure 3-10.

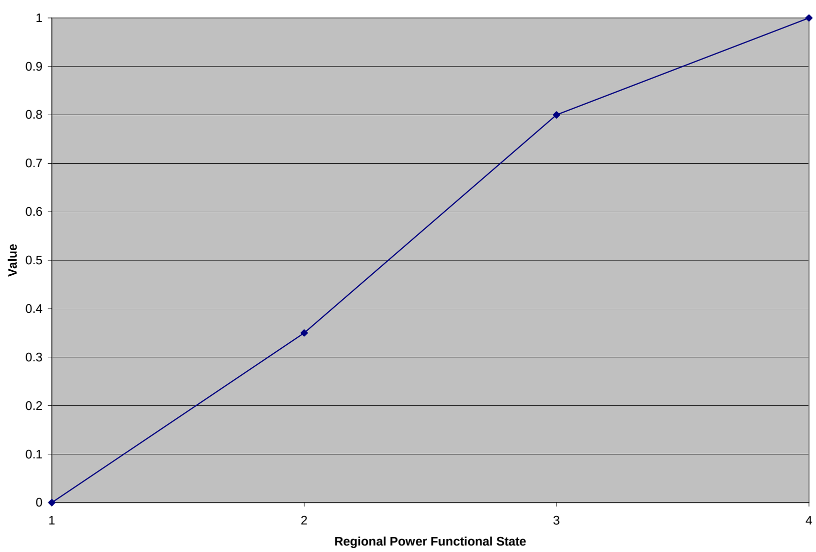

Figure 3-10. Regional power system value function

For the purposes of this example, each region's power system services four major cities and the value function is used for all three regions. Similarly, a value function is developed for the functional state of each region's health services.

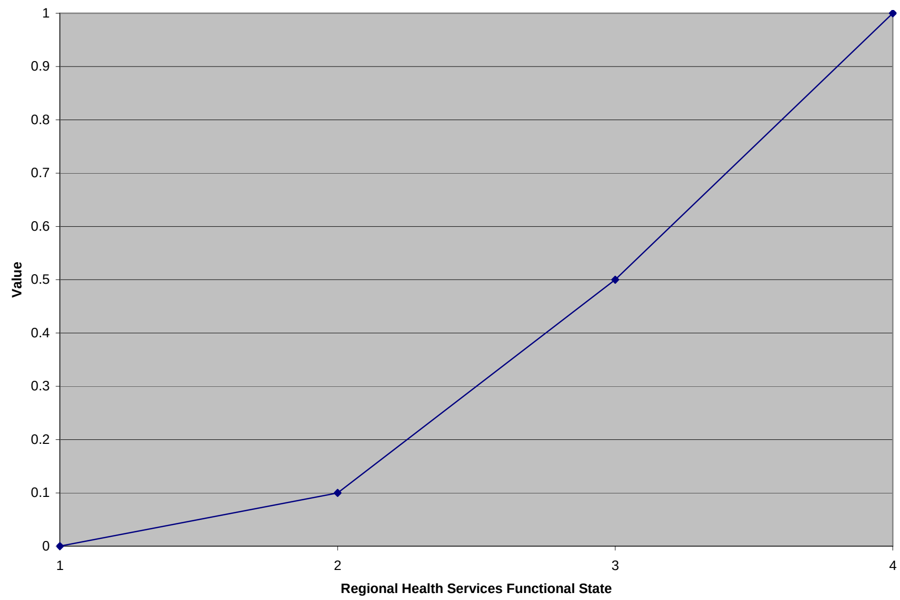

Figure 3-11. Regional health services value function

Planners use the total population size within a given region to determine the weights for O_2. Within Region 2, there are 10 million people living in the four major cities. In Region 1, there are only 5 million people residing within the four major cities. Region 3 has 2 million people residing within the four major cities. Based on the given numbers, the weights are calculated using a swing weighting scheme.

$$w_{2[12]} = (5 \text{ million}/2 \text{ million}) * w_{2[14]} = 2.5 w_{2[14]}$$

$$w_{2[13]} = (10 \text{ million}/2 \text{ million}) * w_{2[14]} = 5 w_{2[14]}$$

$$w_{2[12]} + w_{2[13]} + w_{2[14]} = 1$$

$$2.5 * w_{2[14]} + 5 * w_{2[14]} + w_{2[14]} = 8.5 * w_{2[14]} = 1$$

$$w_{2[14]} = 1/(8.5) = 0.1176 = 0.12$$

$$w_{2[13]} = 0.588 = 0.59$$

$$w_{2[12]} = 0.294 = 0.29$$

Uniform weighting is assumed for health services with all regions being equally important. The resulting weights are included in Table 3-16.

Table 3-16. Weights for objective value functions

Objective	Weights		
	Region 1	Region 2	Region 3
O_2	$w_{2[12]}$	$w_{2[13]}$	$w_{2[14]}$
	0.29	0.59	0.12
O_3	$w_{3[17]}$	$w_{3[18]}$	$w_{3[19]}$
	0.33	0.33	0.34

There is now enough information to develop an objective value function for each objective. However, in order to assess the value of a resource within the context of all three objectives, a multiple objective value function must be developed. In order to do this, a second set of weights must be developed to capture the relative importance of each objective to the overall campaign. Using commander elicitation, w_1, w_2, and w_3 are stated as 0.4, 0.2, and 0.4, respectively. Multiplying the objective weights, w_i, by the regional weights, $w_{i[-]}$, the final weights within the value function can be calculated.

Table 3-17. Weights for multiple objective value function

Objective	Objective Weights	Regional Weights			Final Weights (w_i*$w_{i[-]}$)		
		1	2	3	1	2	3
O_1	w_1	$w_{1[7]}$	$w_{1[8]}$	$w_{1[9]}$	$w_{1[7]}$	$w_{1[8]}$	$w_{1[9]}$
	0.4	0.33	0.33	0.34	0.13	0.13	0.14
O_2	w_2	$w_{2[12]}$	$w_{2[13]}$	$w_{2[14]}$	$w_{2[12]}$	$w_{2[13]}$	$w_{2[14]}$
	0.2	0.29	0.59	0.12	0.06	0.12	0.02
O_3	w_3	$w_{3[17]}$	$w_{3[18]}$	$w_{3[19]}$	$w_{3[17]}$	$w_{3[18]}$	$w_{3[19]}$
	0.4	0.33	0.33	0.34	0.13	0.13	0.14

The multiple objective value function is developed by incorporating the final weights.

It is assumed that each node is in its fully functional state. The value of the initial state of the system is calculated using the multiple objective function.

Table 3-18. Initial value of the system

Objective	End State	$w_i * w_{i[-]}$	$N_{[-]}^{(F)}$	Initial Value
O_1	$N_{[7]}^F$	0.13	3	0
	$N_{[8]}^F$	0.13	3	0
	$N_{[9]}^F$	0.14	3	0
O_2	$N_{[12]}^F$	0.06	4	1
	$N_{[13]}^F$	0.12	4	1
	$N_{[14]}^F$	0.02	4	1
O_3	$N_{[17]}^F$	0.13	4	1
	$N_{[18]}^F$	0.13	4	1
	$N_{[19]}^F$	0.14	4	1
			Value	**0.6**

Table 3-10 contains the resource packages used to achieve O_1. However, the associated indirect effects and cascading effects for each resource package were not considered in the single objective example since the focus was solely on the achievement of O_1.

In the current example, the additional effects that are caused by the selected resource packages must be considered. In this case, the information operations team disables power to Region 2's S-A defenses. However, the action also disables power to one of the major cities within the region (E_{21}) which, in turn, disrupts the local hospital services within that city (E_{31}). Table 3-19 captures direct, indirect, and cascading effects caused by the actions within each resource package.

Table 3-19. Resource packages, effects, and quantities

Resource Package	Effect	F-15	F-16	EA-6B	Info Ops	SOF
R_{11}	E_{11}	8	8	4	0	0
	E_{15}	X	X	X	0	0
R_{12}	E_{12}	0	0	0	1	0
	E_{21}	0	0	0	X	0
	E_{31}	0	0	0	X	0
R_{13}	E_{13}	0	0	0	0	1

Value calculations are summarized for both cases within Table 3-20. If an effect is not produced for a given functional state, a "-" is placed within the E_{ij} column. The ΔV column represents the change in value for each functional state resulting from a produced effect. Since a "-" represents no effect for a given functional state, there is no change in value (represented as a "0").

Table 3-20. Case 1 and Case 2 results

Objective	End State	Initial		Case 1		Case 2	
		$N_{[i]}^{(F)}$	Value	E_{ij}	$\Delta V_{[i]}$	E_{ij}	$\Delta V_{[i]}$
O_1	$N_{[7]}^{F}$	3	0	E_{11}	1	E_{11}	1
	$N_{[8]}^{F}$	3	0	E_{12}	1	E_{12}	1
	$N_{[9]}^{F}$	3	0	E_{13}	0.75	E_{13}	0.75
				E_{15}	0.25	E_{15}	0.25
O_2	$N_{[12]}^{F}$	4	1	-	0	-	0
	$N_{[13]}^{F}$	4	1	-	0	E_{21}	-0.2
	$N_{[14]}^{F}$	4	1	-	0	-	0
O_3	$N_{[17]}^{F}$	4	1	-	0	-	0
	$N_{[18]}^{F}$	4	1	-	0	E_{31}	-0.5
	$N_{[19]}^{F}$	4	1	-	0	-	0
		Value	0.6	Delta	0.4	Delta	0.31

In Case 1, indirect effects and cascading effects are not taken into account. For Case 2, all effects are considered. In both cases, there is an overall positive change in value by producing the effects. However, in Case 2, the additional effects cause a negative change in the value for O_2 and O_3 (as expected). Therefore, the overall change in value produced by the effects is lower (0.31).

In order to determine the value of each resource in terms of the three objectives, the value produced by each effect is divided by the number of resource types. The results of this step are captured in Table 3-21.

Table 3-21. Value of different resource types per effect

Effect	$w_{[i]}$	$V_{[i]}(E_{ij})$	$V_{[i]}$(F-15)	$V_{[i]}$(F-16)	$V_{[i]}$(EA-6B)	$V_{[i]}$(Info Ops)	$V_{[i]}$(SOF)
E_{11}	0.13	1	0.33	0.33	0.34	0	0
E_{12}	0.13	1	0	0	0	1	0
E_{13}	0.14	0.75	0	0	0	0	0.75
E_{15}	0.14	0.25	0.08	0.08	0.09	0	0
E_{21}	0.12	-0.2	0	0	0	-0.2	0
E_{31}	0.13	-0.5	0	0	0	-0.5	0

For both Case 1 and Case 2, the value of each resource type is calculated using the weights and values in Table 3-20. The resource type values are then divided by the quantity of each resource to determine the value of a single resource within the context of the three objectives.

Table 3-22. Resource values for Case 1 in terms of all three objectives

Resource Type	F-15s	F-16s	EA-6Bs	Info Ops	SOF Forces
Value (Type)	0.054	0.054	0.057	0.130	0.105
Value (Unit)	0.007	0.007	0.014	0.130	0.105

Table 3-22 contains the resource values for Case 1. By only accounting for the contributions of direct effects, an individual information operations team still provides the most value to the achievement of the three objectives. The contributions of a single special operations team is second, followed by an EA-6B. The F-15s and F-16s are last and considered equally important since they participated in the same actions, used an equal amount of resources, and were considered equally important to the effects they collectively produced (E_{11} and E_{15}).

Table 3-23. Resource values for Case 2 in terms of all three objectives

Resource Type	F-15s	F-16s	EA-6Bs	Info Ops	SOF Forces
Value (Type)	0.054	0.054	0.057	0.041	0.105
Value (Unit)	0.007	0.007	0.014	0.041	0.105

Table 3-23 contains the resource values for Case 2. Due to the negative contributions of E_{21} and E_{31} to the attainment of O_2 and O_3, the individual operations team now has the least important resource value in terms of resource type. From a value per resource type and value per unit resource standpoint, the special operations team is now the most important resource. From a value per unit resource standpoint, the information operations team is second, followed by the EA-6B. The F-15s and F-16s still contribute the least amount of value per unit resource due to the quantities required to produce the effect.

Using the examples in this section, the methods within this section can be used to identify the value of each resource, in terms of resource type and unit resource, to the achievement of campaign objectives. However, additional methods are required to identify conflicting objectives, identify competing objectives, and use the information to develop improved courses of action (i.e., resource package selections) to better achieve campaign objectives.

3.5. Identifying Conflicting Objectives

Objectives conflict with one another when the attainment of one objective leads to the reduction in attainment of a second objective. In general, the level of conflict between objectives is dictated by the node being influenced or the types of relationships between nodes.

In some cases, the physical, functional, or behavioral state of a given node may be used to represent the objective end state for different objectives with opposing intents. For example, two objectives are considered for a campaign. The first objective is “Destroy all nuclear, biological, and chemical production facilities in the region.” The second objective is “Preserve regional power production services for the duration of the conflict.”

Within the country, there are two nuclear power plants that are also suspected of being used as nuclear weapons research and development sites. In this case, the physical states of both nuclear plants are used as objective end states for the first objective. However, the functional states of both nuclear plants, which are influenced by the physical states of the nuclear plants, are used as objective end states for the second objective. In order to achieve the first objective, both nuclear plants would have to be physically destroyed (a tricky proposition). However, by taking this course of action, both nuclear plants would be reduced to a non-functional state. This course of action would cause a reduction in the level of attainment for the second objective.

In other cases, the relationships between nodes cause two objectives to be in conflict. In the previous section, E_{21} and E_{31} were examples of an indirect effect and cascading effect produced by R_{112}, a resource package designed to produce E_{12} to help achieve O_1. R_{112} included the resources for a pre-defined course of action within an existing operational plan. The effects produced by R_{112} caused an improvement in O_1 but reduced the degrees of attainment for O_2 and O_3. In this case, using the courses of action within the existing operational plan, O_1 and O_2 were considered conflicting objectives. Similarly, O_1 and O_3 were also considered conflicting objectives.

The following steps can be used to identify the source of conflict between two objectives. The process is based on using the state model and the objective end states together to identify the source of conflict and is designed to help a planner think about the system in a logical, systematic way.

Step 1: Develop interaction table of resource packages and objective end states

Step 2: Identify objective end state relationships at highest level of aggregation

Step 3: Evaluate objective end states at the next lowest level of aggregation

Step 4: Repeat step 3 until all conflicting relationships are identified

At first glance, Steps 3 and 4 appear to imply that the planner will be able identify all of the cascading effects by continually dropping down to lower levels of aggregation. However, this is not realistic for two reasons. First, the state model is only as good as the assumptions that are used to build it. Second, intelligence, surveillance and reconnaissance collection capabilities may not be able to provide enough information to accurately model the enemy system and capture all the relationships between nodes.

The first step begins by identifying all n objective end states, the courses of action, and the desired effects for each objective. An interaction table is built using this information and captures the possible impact of a desired effect on the objective end states.

The three objective example in Section 3.4 is used once again to step through conflicting objective identification for an existing operational plan. As a review, the objectives and corresponding objective end states are:

Table 3-24. Objectives and objective end states

O_i	Description	State Representations
O_1	Gain and maintain air supremacy within the theater of operations	$N^F_{[5]}$
O_2	Preserve utilities within the theater of operations	$N^F_{[11]}$
O_3	Preserve public health care services within the theater of operations	$N^F_{[16]}$

Additionally, the resource packages and desired effects are

Table 3-25. Resource packages and desired effects

Resource Package	Description of Actions	Direct Effects
R_{111}	Strike package conducts kinetic strikes against 2 SAM launchers in Region 1	E_{11}
		E_{15}
R_{121}	Information operations accesses SCADA system to disable power to Region 2's S-A defenses	E_{12}
R_{131}	SOF team disables a SAM launcher in Region 3	E_{13}

Based on the information in the previous two tables, an interaction table is constructed (see Table 3-26) to determine the impacts of a given desired effect to the attainment of each objective, represented by its corresponding objective end state(s).

Table 3-26. Example interaction table

Resource Package	O_1	O_2	O_3
	$N^F_{[5]}$	$N^F_{[11]}$	$N^F_{[16]}$
$\mathbf{R_{111}}$	+	N/A	N/A
$\mathbf{R_{121}}$	+	?	?
$\mathbf{R_{131}}$	+	N/A	N/A

If an effect improves the level of achievement for a given objective, a "+" is entered in the appropriate column. If an effect does not impact the level of achievement for a given objective, "N/A" is entered. If an effect degrades the level of achievement for a given objective, a "-" is entered (a "-" identifies a conflict between objectives when this effect is produced). If a planner does not have enough information to determine the relationship between an effect and a given objective end state, "?" is entered.

In this case, all of the effects are produced to improve O_1's degree of achievement. Therefore, the $N_{[5]}^{(F)}$ column contains "+" for each effect. For E_{11} and E_{15}, the kinetic strikes are planned for 2 SAM launchers within Region 1. Planners are able to determine that the SAM launchers are not near any civilian structures. Therefore, E_{11} and E_{15} are assessed as having no impact on the attainment of O_2 and O_3 ("N/A"). For E_{13}, a special operations team is used to disable a SAM launcher in Region 3. This surgical action is not assessed as having any impact on the attainment of O_2 and O_3 ("N/A"). However, there is insufficient information at this level of aggregation to assess E_{12}'s impact on the attainment of O_2 and O_3 ("?").

At this point, no conflicting objectives have been identified. E_{11}, E_{13}, and E_{15} require no further exploration. However, a second interaction table is built at the next lowest level of aggregation to focus on E_{12}'s impacts to O_2 and O_3. The objective end states at this level of aggregation are

Table 3-27. Objective end states at the next lowest level

O_i	Description	State Representations
O_2	Preserve utilities within the theater of operations	$N^F_{[12]}$, $N^F_{[13]}$, $N^F_{[14]}$
O_3	Preserve public health care services within the theater of operations	$N^F_{[17]}$, $N^F_{[18]}$, $N^F_{[19]}$

The "new" objective end states are the functional states of the power system and health system within Regions 1-3. Based on available information, planners are able to assess that the SCADA system only controls the power system within Region 2. Therefore, the planners assess no potential impacts to the power systems or health services in Regions 1 and 3 ("N/A"). However, there is still insufficient information at this level of aggregation to determine E_{12}'s impacts to Region 2's health and power systems ("?").

Table 3-28. Interaction table at the next lowest level

Resource Package	O_2			O_3		
	$N^F_{[12]}$	$N^F_{[13]}$	$N^F_{[14]}$	$N^F_{[17]}$	$N^F_{[18]}$	$N^F_{[19]}$
R_{121}	N/A	?	N/A	N/A	?	N/A

The process is repeated. After the next iteration, planners determine a link between the SCADA system and the local hospital services. It is determined that the distribution system that provides power to Region 2's S-A defenses also provides power to one of the major cities within the region (modeled by $N^F_{[25]}$). It is further determined that the hospitals within the city would be crippled without the city's power services. Therefore, at the next lowest level of aggregation, Table 3-29 helped the planners identify a conflicting relationship between O_1 and the remaining two objectives. Two new effects, E_{21} and $E_{31,}$ are assigned to R_{12} in an effort to capture the negative impacts to O_2 and O_3 by selecting this resource package.

Table 3-29. Final interaction table at lowest level

Resource Package	O_2			O_3		
	$N^F_{[25]}$	$N^P_{[26]}$	$N^B_{[27]}$	$N^F_{[25]}$	$N^P_{[45]}$	$N^B_{[46]}$
R_{121}	-	N/A	N/A	-	N/A	N/A

In this example, the conflict between objectives was created by the actions that were enabled by R_{121}. By identifying the source of the conflict, other courses of action can be explored to eliminate or minimize the impacts of a conflict between two objectives.

The process is simple, but not perfect. The strengths of this process are its ease of use and its ability to rapidly focus on manageable subsets of the system to determine objective relationships. However, as previously stated, the accuracy of this process is a function of the planner's knowledge of the system and the accuracy of the state model.

While the focus of this section is identifying conflicting objectives, this technique can be used to identify any indirect effects or cascading effects that may be caused by a given action or set of actions. By performing this type of analysis, a planner can develop a more complete set of effects that result from an action or actions. Additionally, the analysis helps a planner gain an improved understanding of potential system behaviors.

3.6. Integer Program for Resource Allocation

In the previous two sections, an existing operational plan defined the effects, actions, and resources used to achieve campaign objectives. Under those conditions, the value of a resource was expressed in terms of the resource's ability to support the operational plan. Additionally, conflicting relationships between objectives existed due to the specific courses of action and resources defined by the operational plan.

In this section, resource allocation in a dynamic environment is considered. Suppose a commander and his staff are now engaged in two simultaneous conflicts within the commander's area of responsibility. Further, suppose a commander has similar objectives, objective end states, resource types, and value functions for both conflicts. In this example, planners are able to select from a list of possible courses of action that require different resource packages.

As in the real world, the commander's available resources are not sufficient to simultaneously gain and maintain air supremacy in both theaters of operation. Air superiority is equally important to the success of both campaigns, leading to competition for the same resources.

Objectives are said to be competing objectives when their attainment requires the simultaneous use of limited resources. If there are sufficient quantities of a given resource to facilitate the attainment of both objectives, then there is no competitive relationship between objectives. Otherwise, competition exists between objectives for that given resource.

In order to identify competing objectives and the resource types that cause the competitive relationships between objectives, the following process is used.

Step 1: Develop resource packages

Step 2: Construct an integer program for resource package selection

Step 3: Use the integer program to select the resource package combination that maximizes the number of objectives achieved with the minimum number of resources

Step 4: Identify the objectives and subobjectives that are not achieved

Step 5: Identify the resource packages that were not selected for the unachieved objectives and subobjectives

Step 6: Determine the binding resource constraints that prevent the resource packages from being selected

Step 7: Identify the objectives that are associated with the binding resource constraints

First, different resource packages (R_{ijk}) are developed that correspond to the courses of action created by the planners. In the previous example, the courses of action were limited to only those actions that resulted in the complete achievement of an objective end state. In this example, the original courses of action specified in Table 3-25 are expanded to include cases where a course of action can only achieve partial success toward objectives attainment. With limited resources, it is probable that courses of action and their associated resources packages will cause only a partial improvement to achieving air superiority. Table 3-30 includes the resource packages and description of actions for each course of action.

Table 3-30. Resource packages and descriptions of actions

Resource Package	Description of Actions
$\mathbf{R_{111}}$	Kinetic air strikes to drive a region's S-A defenses to a **non-functional state**
$\mathbf{R_{112}}$	Kinetic air strikes to drive a region's S-A defenses to a **partially functional** state
$\mathbf{R_{113}}$	IO team controls SCADA system and disables power to drive a region's S-A defenses to a **non-functional state**
$\mathbf{R_{114}}$	SOF teams drive a region's S-A defenses to a **non-functional state**
$\mathbf{R_{115}}$	SOF team drives a region's S-A defenses to a **partially functional state**

The resource types and quantities in Table 3-31 are different for each resource package. Munitions types and enabling capabilities (e.g., GPS, Link-16) are not included within the example but could be modeled in similar fashion.

Table 3-31. Resource quantities

Resource Package	F-15	F-16	EA-6B	Info Ops	SOF
$\mathbf{R_{111}}$	8	8	4	0	0
$\mathbf{R_{112}}$	4	4	2	0	0
$\mathbf{R_{113}}$	0	0	0	1	0
$\mathbf{R_{114}}$	0	0	0	0	2
$\mathbf{R_{115}}$	0	0	0	0	1

After all possible resource packages are identified for each objective end state, an integer program is developed to assist the planners with course of action selection. In this example, planners want to maximize the degree of achievement of air superiority in both theaters using the minimum number of resources. Therefore, the general form of the objective function is

$$max \sum_{\forall i} w_i \cdot V(O_i)$$

where

w_i – weight associated with objective i
$V(O_i)$ – value function to assess degree of achievement for objective i

Objective functions can be numerous and take many forms. For example, each campaign could have its own objective function. In this case $w1_i$ and $V1_i(O1_i)$ correspond to the first campaign while $w2_i$ and $V2_i(O2_i)$ correspond to the second campaign.

$$max \sum_{\forall i} w1_i \cdot V1(O1_i)$$

$$max \sum_{\forall i} w2_i \cdot V2(O2_i)$$

The objective functions can also be expressed as minimizing the relative distance between the current system state and the desired end state. The weights of each multiple objective value function are summed to determine $V1^*$ and $V2^*$, the value of going from the current system state, A^0, to the system's desired end state, A^*. $V1^*$ and $V2^*$ are the sum of the weights since the single dimensional value functions are all normalized from 0 to 1. The objective functions take the form

$$\min \ (V1^* - \sum_{\forall i} w1_i \cdot V1(O1_i))$$

$$\min \ (V2^* - \sum_{\forall i} w2_i \cdot V2(O2_i))$$

Other objective function forms are also possible. Regardless of the form used, objective functions are subject to constraints. In this case, there are three general types of constraints—resource supply constraints, effect constraints, node constraints, and value constraints. Supply constraints define the total number of resource packages that can be selected. The constraints take the form

$$\sum_{a}(r_{ijka} \cdot R_{ijk}) \leq R_a$$

where r_{ijka} is the quantity of resource type a that is required for R_{ijk}. R_a is the total available quantity of resource type a. For example, the supply constraints for the resource packages in Table 3-30 take the form

F-15s:	$8R_{111}$	+	$4R_{112}$								$\leq$	R_1
F-16s:	$8R_{111}$	+	$4R_{112}$								$\leq$	R_2
EA-6Bs:	$4R_{111}$	+	$2R_{112}$								$\leq$	R_3
Info Ops:				+	R_{113}						$\leq$	R_4
SOF:						+	$2R_{114}$	+	R_{115}		$\leq$	R_5

The R_a values establish the bounds for the number of resource packages that can be selected. The resource supply constraints are the foundation of the integer program since resource package selection ultimately determines the number of objectives that can be achieved.

Effect constraints limit the total number of resource packages that are selected using the values of the effects that are produced by each resource package. The value is expressed in terms of the single dimensional value functions of the nodes that represent the objective end states for a given objective. There is one effect constraint for each objective end state.

Since the single dimensional value functions are normalized between 0 and 1, it is not possible to obtain greater than a value of 1 for achieving the desired state for an objective end state. Therefore, each effect constraint is necessary to ensure that the cumulative value of the produced effects against an objective end state do not exceed 1. Each effect constraint takes the form

$$\sum_{\substack{\forall R_{ijk} \\ \text{against } N^F_{[-]}}} V_{[-]}(\Delta N^F_{[-]}) \cdot R_{ijk} \leq 1$$

For example, the resource packages identified in Table 3-31 are used to drive each region's S-A defenses in one of the campaigns from a fully functional state to a non-functional state. The first resource package, R_{111}, enables kinetic strikes that destroy two of the SAM launchers in Region 1 (n_1 and n_2 in Figure 3-3). The second course of action, enabled by R_{134}, is used to disable two of the SAM launchers in Region 3 (n_3 and n_4 in Figure 3-3). Both actions expose the northern part of the country to allow freedom of action for all coalition air operations.

Using each region's single dimensional value function to express a resource package's value, R_{111} is worth 1 unit of value for driving Region 1's S-A defenses to a non-functional state and an additional 0.25 value for driving Region 3's S-A defenses to a partially functional state. Similarly, R_{134} gains maximum value for driving Region 2's S-A defenses to a non-functional state.

In each case, the scoring of each resource package is independent of the effects of the other resource packages. R_{111} and R_{134} collectively score a value of 1.25 for Region 3 even though the maximum achievable value is 1. Without the effect constraints, the selected resource packages are enabling more actions than are necessary to achieve the objective end states for Regions 1 and 3.

Table 3-32. Example of an inefficient resource package mix

Region	Single Dimensional Value		
	R_{111}	R_{114}	Total
1	1	0	1
3	0.25	1	**1.25**

The effect constraints are required to ensure the selected resource packages do not exceed a value of 1 for a given objective end state. For this example, the effect constraints are written as

Region 1: $R_{111} \leq 1$
Region 3: $0.25\ R_{111} + R_{134} \leq 1$

R_{111} is not selected when the effect constraints are used. Therefore, other courses of action and corresponding resource packages are required to ensure air supremacy is achieved in Region 1.

While the effect constraints ensure the selected resource packages do not exceed a value of 1 for a given objective end state, there are no constraints in place to prevent multiple resource packages from influencing the same node. Node constraints are introduced to account for this possibility. There is one constraint for each node that is used to represent a given objective.

$$\sum_{\substack{\text{all } R_{ijk} \\ \text{against node}}} R_{ijk} \leq 1$$

For example, SAM launcher 2, or n_2, provides coverage for both Regions 1 and 3. Planners identify 3 resource packages that can be used to achieve air supremacy in both regions. R_{111} enables two strikes against n_1 and n_2 to reduce Region 1's S-A defenses to a non-functional state. R_{132} enables a strike package against n_2 to reduce Region 3's S-A defenses to a partially functional state. R_{134} enables 2 SOF team attacks against n_3 and n_4 to reduce Region 3's S-A defenses to a non-functional state. For this example, it is assumed that there are sufficient resources to select all resource packages. The effect constraints in this example are

$$\begin{array}{llllll} \textbf{Region 1:} & R_{111} & & & \leq & 1 \\ \textbf{Region 3:} & 0.25\ R_{111} & +\ 0.25\ R_{132} & +\ R_{134} & \leq & 1 \end{array}$$

Using these constraints, the integer program selects R_{111} and R_{132}.

Table 3-33. Selected resource packages

Region	Single Dimensional Value		
	R_{111}	R_{132}	Total
1	1	0	1
3	0.25	0.25	0.5

However, both R_{111} and R_{132} enable actions against n_2. The integer program is selecting an inefficient set of resource packages and is overvaluing the collective contributions of R_{111} and R_{132}. Region 3 is driven to a partially functional state following the actions against n_2. The cumulative effects of R_{111} and R_{132} should only result in a value of 0.25, not 0.50. To prevent this inconsistency from occurring, the following node constraints are introduced.

$$\begin{array}{llllll} \textbf{Node 1:} & R_{111} & & & \leq & 1 \\ \textbf{Node 2:} & R_{111} & +\ R_{132} & & \leq & 1 \\ \textbf{Node 3:} & & & R_{134} & \leq & 1 \\ \textbf{Node 4:} & & & R_{134} & \leq & 1 \end{array}$$

With the effect constraints and the node constraints in place, R_{111} is the only resource package selected. Other courses of action and resource packages are required to achieve air supremacy in Region 3 (e.g., creating R_{133} to strike n_3).

Value constraints are then used to ensure the value of the cumulative effects do not exceed 1 for each level of an objective hierarchy (i.e., each level of aggregation). For example, both campaigns in this section are considered to be equally important and use the same objectives hierarchy that is captured in Figure 3-12.

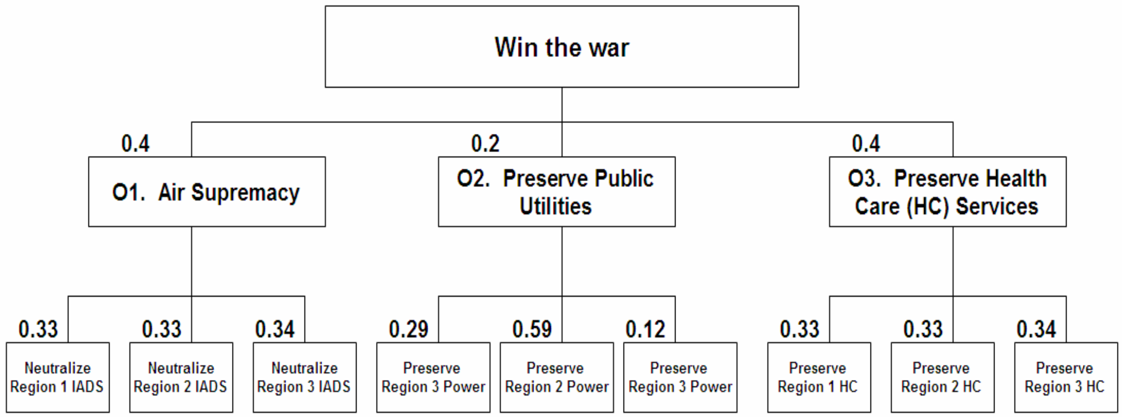

Figure 3-12. Notional objectives hierarchy for a single campaign

The first set of value constraints ensures that the value of the cumulative effects does not exceed the maximum possible value for each objective (O_1, O_2, and O_3). In this case, 1 is the maximum value for each objective.

$$\sum_{\forall[-]} w_{[-]} \cdot V_{[-]}(\Delta N_{[-]}^{F}) \leq 1$$

For the objectives in Figure 3-12, the first set of value constraints are

$$\begin{array}{llllllll}
\mathbf{O_1\ Value:} & 0.33V_{[7]}(\Delta N_{[7]}^{F}) & + & 0.33V_{[8]}(\Delta N_{[8]}^{F}) & + & 0.34V_{[9]}(\Delta N_{[9]}^{F}) & \leq & 1 \\
\mathbf{O_2\ Value:} & 0.29V_{[12]}(\Delta N_{[12]}^{F}) & + & 0.59V_{[13]}(\Delta N_{[13]}^{F}) & + & 0.12V_{[14]}(\Delta N_{[14]}^{F}) & \leq & 1 \\
\mathbf{O_3\ Value:} & 0.33V_{[17]}(\Delta N_{[17]}^{F}) & + & 0.33V_{[18]}(\Delta N_{[18]}^{F}) & + & 0.34V_{[19]}(\Delta N_{[19]}^{F}) & \leq & 1
\end{array}$$

The second set of value constraints ensures that the value of the cumulative effects does not exceed the maximum possible value of each campaign. The *[-]* subscript corresponds to the objective end states that represent O_1 ($N_{[5]}^{F}$), O_2 ($N_{[11]}^{F}$), and O_3 ($N_{[16]}^{F}$).

Campaign Value: $0.4V_{[7]}(\Delta N^F_{[7]}) \quad + \quad 0.2V_{[8]}(\Delta N^F_{[8]}) \quad + \quad 0.34V_{[9]}(\Delta N^F_{[9]}) \;\leq\; 1$

By incorporating the four types of constraints, the integer program selects feasible resource packages that maximize the number of objectives that are achieved. However, there are still potential problems when calculating total objective value that need to be addressed. For example, suppose the planners consider two resource packages to achieve air supremacy in Regions 1 and 3. R_{111} enables strikes against two SAM launchers (n_1 and n_2 in Figure 3-3) to achieve air supremacy in Region 1. R_{112} enables strikes against a single SAM launcher (n_3). Independent of other resource package selections, this course of action drives Region 3's S-A defenses to a partially functional state and gains a value of 0.25. When combined, the actions enabled by R_{111} and R_{112} drive the S-A defenses in Regions 1 and 3 to non-functional states. These actions should result in gaining 1 unit of value for each region's functional state. However, by scoring each resource package independently, only 0.5 units of value are gained for Region 3.

Table 3-34. Undervaluing R_{111} and R_{112}

Region	Single Dimensional Value		
	R_{111}	R_{112}	Total
1	1	0	1
3	0.25	0.25	**0.5**

Such logic can also lead to inefficient course of action selections. Even though n_2 and n_3 are already disabled and Region 3's S-A defenses are considered non-functional, up to two additional resource packages that each score 0.25 for Region 3 may still be selected.

Therefore, a final set of constraints are added to ensure that the integer program does not select more resource packages than are required. In Section 3.4.1, planners stated that an IADS region is non-functional if two of its SAM launchers were disabled. The following constraints are added for each region to ensure the minimum number of resource packages are selected to achieve air supremacy in both campaigns.

$$\sum R_{ijk} \leq 2$$

The constraint for Region 3, for example, only includes resource packages (R_{ijk}) that are designed to disable the SAM launchers that cover Region 3 (n_2, n_3, and n_4).

The integer program is designed to select the resource packages that achieve the greatest degree of attainment of both campaigns' objectives. Binding resource constraints prevent the achievement of all objectives. By examining these constraints, the planners can identify the specific objectives that are competing for the limited resources.

Therefore, slack variables are added to the integer program. Slack variables, S_a, identify instances of excess quantities of resource type a. For the purposes of this formulation, slack variables are non-negative, integer values. If $S_a > 0$, there are excess quantities of resource type a. If there are sufficient quantities of the other resource types, then all campaign objectives within both campaigns are met. In this case, there objectives will not compete for the same resources.

However, if $S_a = 0$, a resource limitation may exist for the given resource type. In this case, there are either exactly enough resources or insufficient resources to achieve the campaign objectives in both conflicts. If any of the objectives that require this resource type are not met and $S_a = 0$, the resource type is a possible binding constraint.

The addition of slack variables does not affect the objective function; however, the supply constraints are modified in the following manner. The original supply constraints were originally expressed as inequality constraints.

$$\Sigma r_{ijka} R_{ijk} \leq R_a$$

Slack variables are introduced to balance the left and right hand sides of the original inequality constraints. The modified resource constraints take the following form.

$$\Sigma r_{ijka} R_{ijk} + S_a = R_a$$

In the following example, the commander wants to gain and maintain air supremacy while preserving utilities and health care services in both areas of operation. As was previously stated, the same objective end states are used for both conflicts. This leads to 18 objective end states, 6 of which describe air supremacy in both theaters (the functional states of the S-A defenses in Regions 1, 2 and 3). Each resource package that is identified in Table 3-30 can be used against each node within each region, leading to 74 resource package alternatives. Each alternative produces its desired effect. Other indirect effects and cascading effects are randomly added to some of the resource alternatives to distinguish between resource package alternatives.

Three different case runs are used in this example with different resource quantities for each resource type.

Table 3-35. Case runs

Resource Package	Case 1	Case 2	Case 3
F-15	20	40	6
F-16	12	40	6
EA-6B	12	16	4
Info Ops	2	6	1
SOF	2	12	2

The first case is a baseline case representing an average distribution of resources. The second case represents a situation where there are excess resources for each resource type. The final case represents a situation in which there are limited quantities of resources. Excel Solver was used to find a solution for each case.

In the baseline case, there were sufficient resources to achieve air supremacy in both campaigns. Table 3-36 identifies the number of resources used in each region.

Table 3-36. Baseline case results

Objective	Region	F-15	F-16	EA-6B	Info Ops	SOF
1	1					1
	2				1	
	3	8	8	4		
2	1					
	2	4	4	2		1
	3				1	
Total Used		12	12	6	2	2

In the excess resource case, there were sufficient resources to achieve air supremacy in both theaters. The final resource package selections were primarily based coefficient values in the objective function and the additional constraints that prohibit resource package selections from gaining more value than is possible. Additionally, no information operations teams or SOF teams were selected.

Table 3-37. Excess case results

Objective	Region	F-15	F-16	EA-6B	Info Ops	SOF
1	1					
	2	8	8	4		
	3	8	8	4		
2	1					
	2	8	8	4		
	3	8	8	4		
Total Used		32	32	16	0	0

The excess case highlights the opportunity for multiple feasible solutions. There may be more than one way to achieve air superiority in both campaigns. While this thesis does not explore optimal resource allocations, two different approaches could be taken to determine the minimum number of resource packages to achieve air superiority in both campaigns. First, a second objective function could be introduced that minimizes the number of selected resource packages.

$$\min \sum R_{ijk}$$

Second, a penalty function could be added to the original objective function that subtracts a small amount of value for each resource package that is used.

$$\max\left(\sum_{\forall i} w_i \cdot V(O_i) - 0.01 \cdot \sum R_{ijk}\right)$$

Since the original objective function is a max function, the penalty function will force the integer program to select the minimum number of resource packages to achieve the most objectives that are possible. Both techniques are left to the reader for further exploration.

In the small quantities case, there are insufficient resources preventing the achievement of air supremacy in both theaters. The resources are divided into three resource packages. In the first campaign, two SOF teams are used to disable two of the SAM launchers (see n_2 and n_7 in Figure 3-3) in Region 1 that also overlap Regions 2 and 3. In the second campaign, one aircraft strike package is used to destroy one SAM launcher (n_7) that overlaps Regions 1 and 2. An information operations team is used to disable two of the SAM launchers in Region 3 (n_2 and n_3). Both actions drive Regions 1 and 3 to a non-functional state while driving Region 2 to a partially functional state.

Table 3-38. Small quantities case

Objective	Region	F-15	F-16	EA-6B	Info Ops	SOF
1	**1**					2
	2					
	3					
2	**1**	4	4	2		
	2					
	3				1	
Total Used		4	4	2	1	2

3.7. Summary

This chapter identified the methodology to determine the value of a resource within the context of campaign objectives, to identify conflicting objectives within a campaign, and to identify objectives that compete for the same resources. Additionally, an integer program was used to select the minimum number of resources to maximize the achievement of campaign objectives. In Chapter 4, these methods and tools will be applied to a stability example that is modeled after current efforts in Iraq.

4. Results and Analysis

4.1. Overview

In this chapter, the methodology from Chapter 3 is applied to a stability operations example. The example is patterned after recent nation-building efforts in Iraq as ample unclassified data is available for use. Section 4.2 contains the objectives hierarchy that is used throughout the remainder of this chapter. Section 4.3 describes the nation-building example and identifies the objective end states for 2 of the 14 subobjectives that are used to demonstrate the application of techniques described in Chapter 3. Section 4.4 captures objective end state identification, value model construction, resource package generation, and mixed integer program development. Section 4.5 describes the process used to determine the value of a resource. Section 4.6 captures the sensitivity analysis of a resource's value with respect changes in the available budget. Section 4.7 contains the process used to identify competing objectives. Section 4.8 describes how the process for identifying conflicting objectives can also be used to identify indirect and cascading effects. Section 4.9 summarizes the key findings after exercising using the methodology.

4.2. Objectives Hierarchy

In this example, the United States and its allies are rebuilding a nation following the end of major combat operations between coalition forces and the nation's previous leadership regime. The objectives and subobjectives were derived from the main objectives of the Coalition Provisional Authority (CPA), the coalition body that governed Iraq from April 2003 through June 2004 (CPA, 2004:2). There are four major objectives to rebuild a sovereign nation (see Figure 4-1).

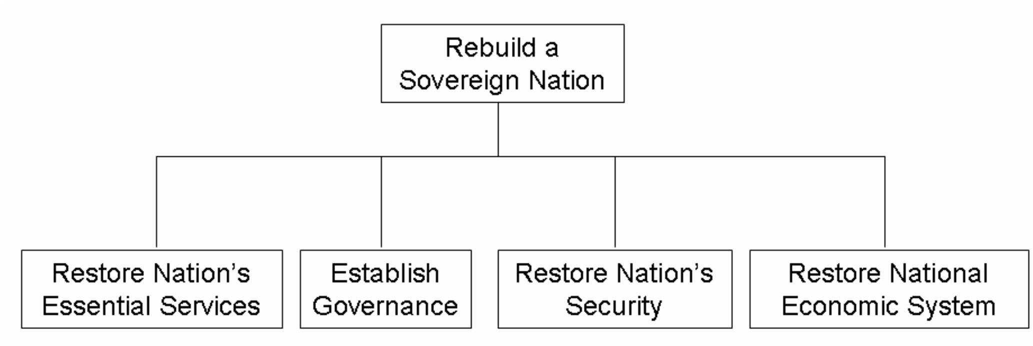

Figure 4-1. Objectives hierarchy

The first objective, *restoring the nation's essential services*, is focused on the restoration of the nation's infrastructure. This objective, O_1, is decomposed into 6 subobjectives:

$O_{1.1}$. Restore the nation's potable water and wastewater systems
$O_{1.2}$. Restore the nation's electrical system
$O_{1.3}$. Restore the nation's transportation system
$O_{1.4}$. Restore the nation's health care system
$O_{1.5}$. Restore the nation's educational system
$O_{1.6}$. Restore and modernize the nation's telecommunications systems

The second objective, *establishing governance*, is focused on the establishment of the nation's political system. O_2 is decomposed into 2 subobjectives:

$O_{2.1}$. Develop the framework and capacity for national elections
$O_{2.2}$. Support the development of national political parties

The third objective, *restoring national security,* is focused on creating a secure and stable environment within the country. O_3 is decomposed into 3 subobjectives.

$O_{3.1}$. Build a national judicial system
$O_{3.2}$. Develop national security forces
$O_{3.3}$. Develop national military forces

The fourth objective, *restoring the national economic system,* is focused on rehabilitating the nation's economy. O_4 is decomposed into 3 subobjectives.

$O_{4.1}$. Build a financial market structure
$O_{4.2}$. Pursue a national strategy for human resources development
$O_{4.3}$. Lay the foundation for an open economy

Figure 4-2 summarizes this hierarchy of objectives and supporting subobjectives.

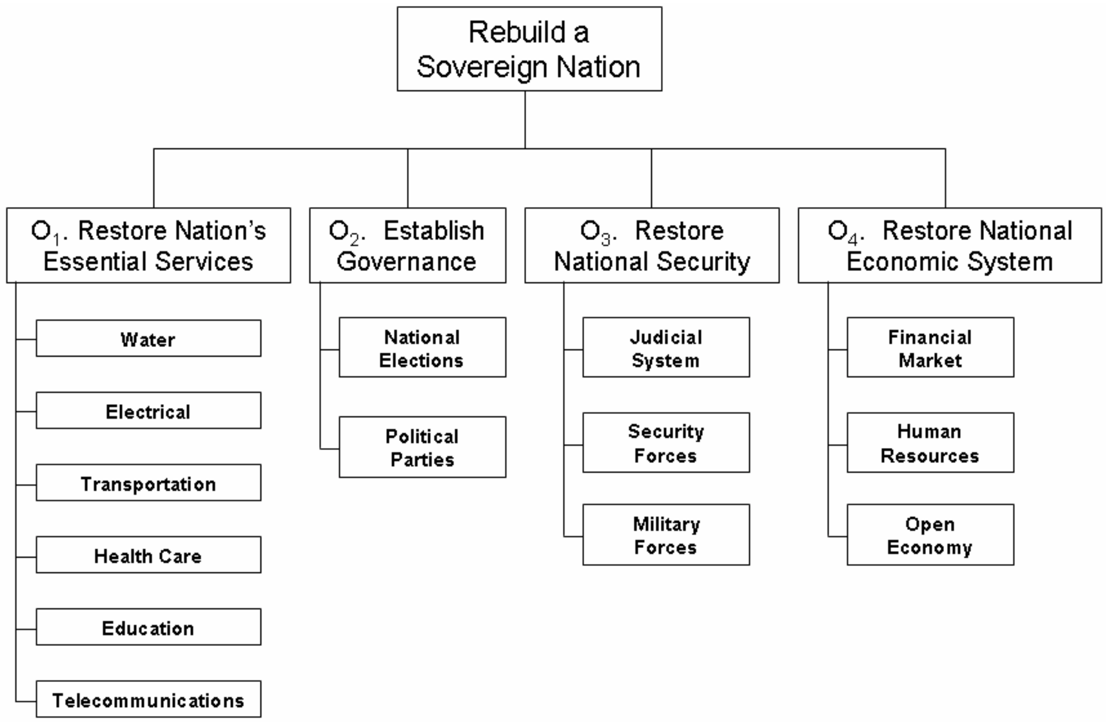

Figure 4-2. Objectives hierarchy with supporting objectives

Coalition officials provide the following preference statements regarding the four main objectives. First, they state that O_3, restoring national security, is the most important objective since it provides a safe environment to conduct actions that support the other three objectives. The remaining three objectives are equally important when compared to each other. During elicitation, coalition officials state that O_3 is 1.2 times as important as O_1, O_2, and O_4. Using swing weighting, the resulting weights are calculated and provided in Table 4-1.

Table 4-1. Weights for main objectives

Objective	Description	Weight
O_1	**Restore Nation's Essential Services**	0.24
O_2	**Establish Governance**	0.24
O_3	**Restore National Security**	0.28
O_4	**Restore National Economic System**	0.24

Within O_1's branch, the 6 subobjectives are viewed as being equally important to each other. Using uniform weighting techniques, the weights for each subobjective are calculated and provided in Table 4-2. $O_{1.3}$ and $O_{1.4}$ weights are both reduced by 0.01 to ensure that the weights sum to 1.

Table 4-2. Weights for O_1's subobjectives

Subobjective	Description	Weight
$O_{1.1}$	**Restore nation's potable water and wastewater systems**	0.17
$O_{1.2}$	**Restore nation's electrical system**	0.17
$O_{1.3}$	**Restore nation's transportation system**	0.16
$O_{1.4}$	**Restore nation's health care system**	0.17
$O_{1.5}$	**Restore nation's education system**	0.16
$O_{1.6}$	**Restore/modernize nation's telecommunications system**	0.17

The subobjectives in O2's branch are also viewed as being equally important. Uniform weighting techniques are used once again to calculate the weights for the two subobjectives (see Table 4-3).

Table 4-3. Weights for O_2's subobjectives

Subobjective	Description	Weight
$O_{2.1}$	**Develop the framework and capacity for national elections**	0.50
$O_{2.2}$	**Support the development of national political parties**	0.50

The subobjectives in O_3's branch are not viewed as being equally important. Coalition officials view the establishment of the nation's security forces, or $O_{3.2}$, as being the most important subobjective within O_3's branch. The remaining subobjectives are viewed as being equally important. During elicitation, the State Department officials views $O_{3.2}$ as being 1.2 times more important than $O_{3.1}$ and $O_{3.3}$. Using swing weighting techniques, the weights are calculated and provided in Table 4-4.

Table 4-4. Weights for O_3's subobjectives

Subobjective	Description	Weight
$O_{3.1}$	**Build a national judicial system**	0.31
$O_{3.2}$	**Develop national security forces**	0.38
$O_{3.3}$	**Develop national military forces**	0.31

The subobjectives for O_4's branch are viewed as being equally weighted. Using uniform weighting techniques, the following weights are calculated and provided in Table 4-4. $O_{4.3}$'s weight is increased by 0.01 to ensure that the weights sum to 1.

Table 4-5. Weights for O_4's subobjectives

Subobjective	Description	Weight
$O_{4.1}$	**Build a financial market structure**	0.33
$O_{4.2}$	**Pursue national strategy for human resources development**	0.33
$O_{4.3}$	**Lay the foundation for an open economy**	0.34

Incorporating the weights, the starting objectives hierarchy for this nation building example is shown in Figure 4.2.

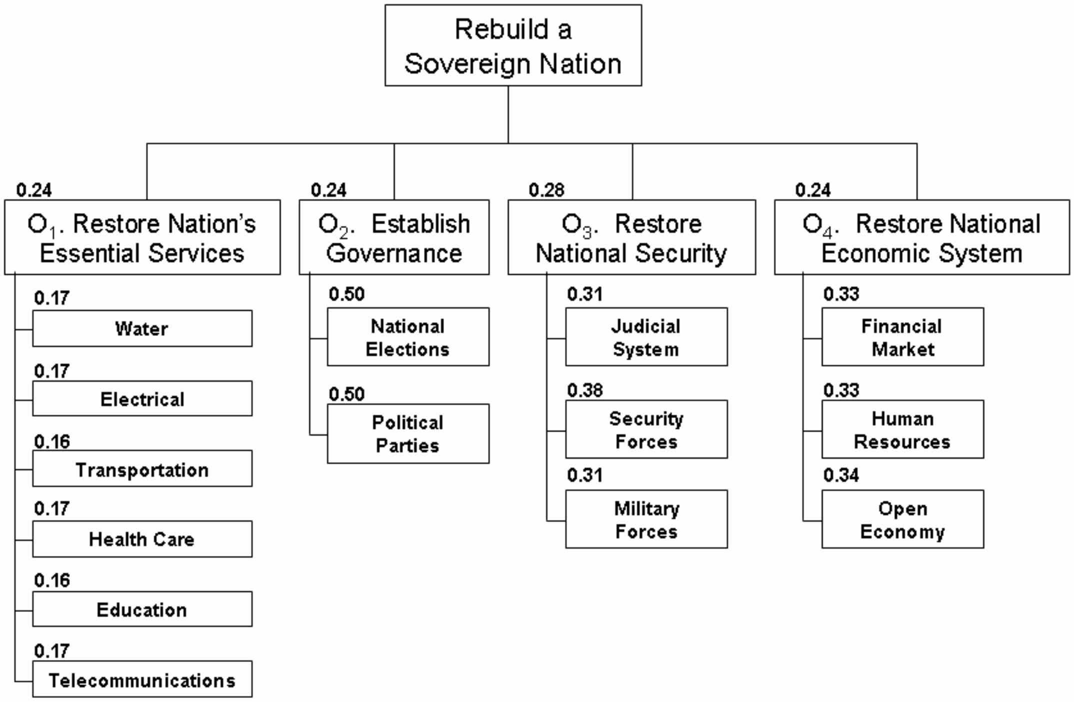

Figure 4-3. Starting objectives hierarchy for nation building example

This hierarchy is used throughout the chapter to determine the best combination of resource packages and to calculate the value of each resource within the combination.

4.3. Scenario Description

The nation contains 9 major cities with different populations. The cities are patterned after 9 major US cities that were selected at random. Population estimates were obtained from US Census Bureau data (US Census Bureau, 2000). City 5 is the nation's capital and is the most heavily populated city within the country.

Table 4-6. City Populations (US Census Bureau, 2000)

Region	City	Patterned After	Population
1	**1**	Phoenix, AZ	1,276,510
	2	Jacksonville, FL	735,617
	3	Houston, TX	1,953,631
2	**4**	Philadelphia, PA	1,517,550
	5	New York City, NY	8,008,278
	6	San Diego, CA	1,223,400
3	**7**	San Francisco, CA	776,733
	8	Chicago, IL	2,896,016
	9	Fort Worth, TX	534,694

In this scenario, the nation has a new government in place, a functioning judicial system, and sufficient numbers of security forces and military forces to provide a stable, secure environment (i.e., O_2 and O_3 have been achieved). Additionally, the water, electrical, transportation, and health care systems are in place to provide acceptable levels of service to the people in each city (i.e., subobjectives $O_{1.1}$, $O_{1.2}$, $O_{1.3}$, and $O_{1.4}$ have been achieved).

The nation's government is now interested in restoring the telecommunications system to pre-war levels and modernizing the system to facilitate future growth. Additionally, the nation's financial market is nearly non-existent due to neglect by the previous leadership regime. Therefore, subobjectives $O_{1.6}$ and $O_{4.1}$ are the focus of rebuilding efforts in this planning horizon.

4.4. Operational Plan Development

In Section 4.2, an objectives hierarchy was developed to capture the preferences of the nation's government and the coalition officials. The government set its priorities for the next planning horizon and placed special emphasis on subobjectives $O_{1.6}$ and $O_{4.1}$.

In order to develop the plan that achieves these objectives, the following steps are required.

Step 1. Identify the objective end states for each objective and subobjective as described in Section 3.4

Step 2. Develop the single dimensional value functions for each subobjective as described in Section 3.4

Step 3. Construct candidate resource packages as described in Section 3.4

Step 4. Build the integer program that is used for resource package selection as described in Section 3.6

Step 5. Determine the best resource package combination(s)

Step 5 is accomplished several times in this chapter to determine the value of a resource, to identify competing objectives, and to perform sensitivity analysis.

4.4.1. Objective End States

First, state representations are identified for the top two tiers of the objectives hierarchy. Each objective and subobjective is modeled using the functional state of an aggregated node that represents a given system (see Figure 4-4).

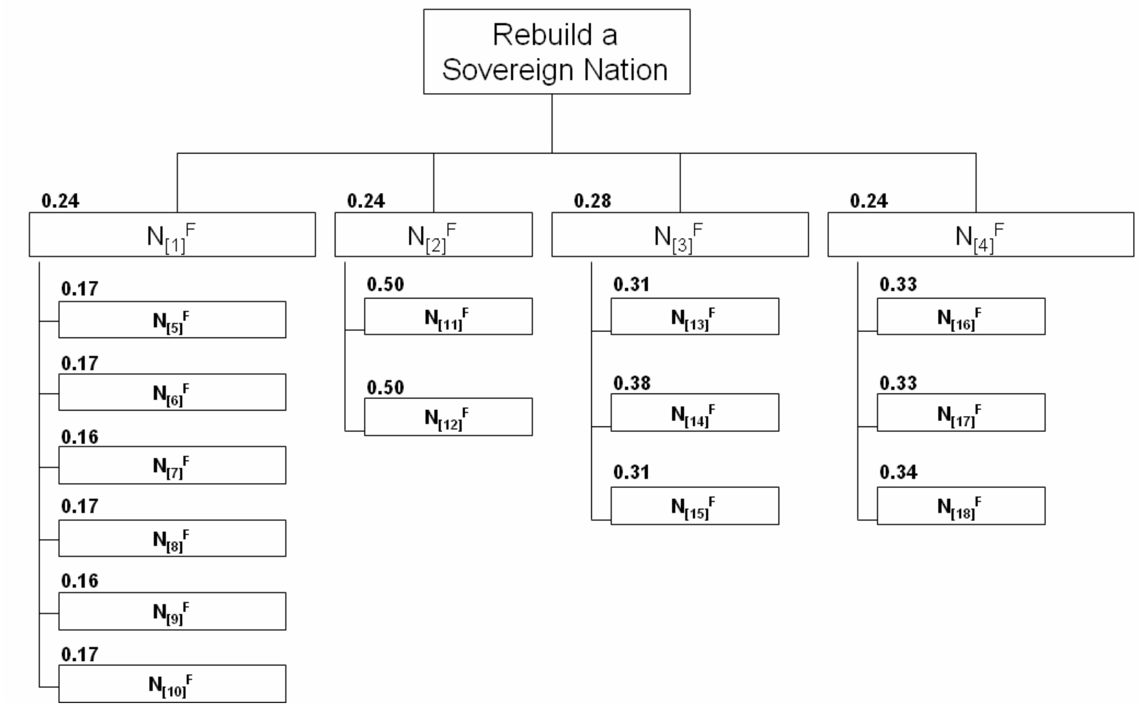

Figure 4-4. State representations for each objective and subobjective

The telecommunications subobjective is represented by $N_{[10]}^F$. For this scenario, the nation's telecommunications system is divided into standard telephone and wireless phone services, a national emergency service, and postal services, based on CPA weekly status reports in 2004 (CPA, 2004b:4).

The weights for the phone services, national emergency service, and postal services subobjectives were calculated using swing weighting techniques. The national phone system and emergency service system are considered equally important. Using Iraq as an example, an article in USA Today reported that "…only 13% of residents say they use the mail" (Eversley and Crain, 2004). Therefore, the postal system is the least important subobjective. The phone system and emergency service system are each viewed as being 1.3 times more important than the postal system. The resulting weights are captured in Figure 4-5.

Most of the CPA's phone service data was reported within the context of improvements to a specific region or city (e.g., installing 12 new telephone exchange switches in Baghdad) or providing new services that improved phone services in all of the cities (e.g., installing a new satellite gateway to facilitate international calling) (CPA, 2004:26). Therefore, the phone system and postal system are decomposed into 3 regions and 9 cities. Uniform weighting techniques were used to weight each region. City weights were calculated by dividing each city's population by the total population of the 3 cities within the given region. The weights are captured in Figure 4-5.

The national emergency service is an emergency radio service that allows firefighters and police officers to communicate with each another during crisis operations (CPA, 2004:26). The CPA provided data in terms of the number of handheld, mobile, and base radio systems for the police and firefighters. Similar to phone services, the national emergency system is decomposed into three regions. The regions are decomposed into police and fire radio systems. Uniform weighting techniques were used to calculate the weights for each region and the weights between each region's police and fire radio systems. The complete telecommunications decomposition is captured in Figure 4-5.

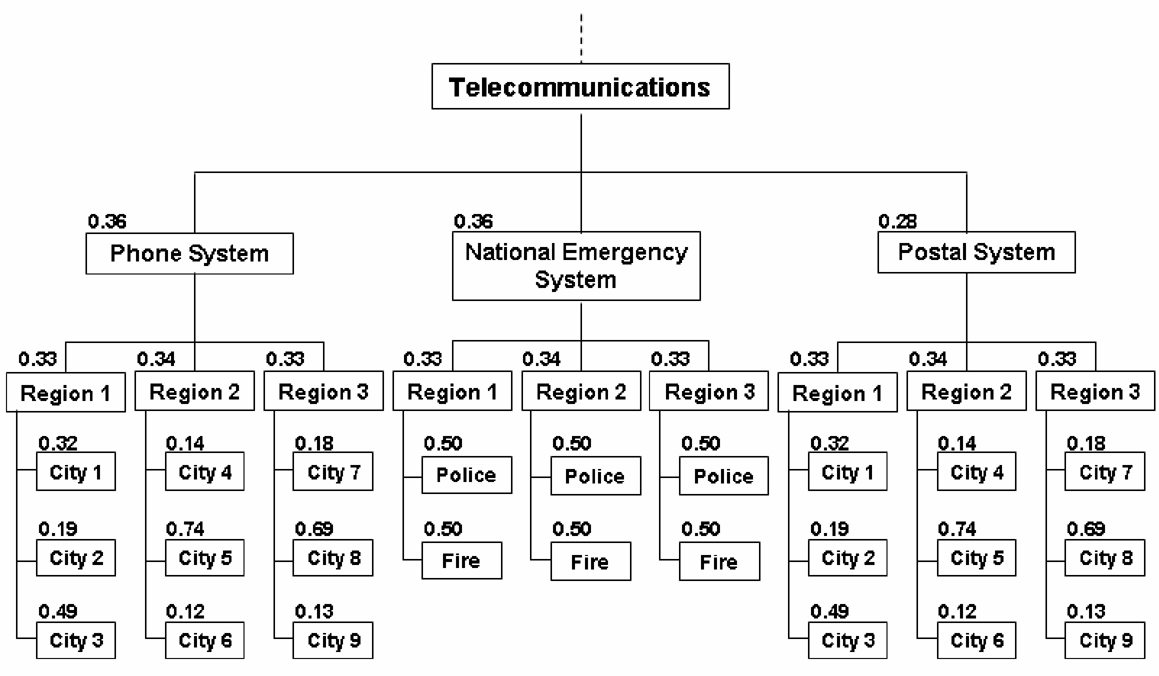

Figure 4-5. Telecommunications subobjective decomposition

The state representation is captured in Figure 4-6.

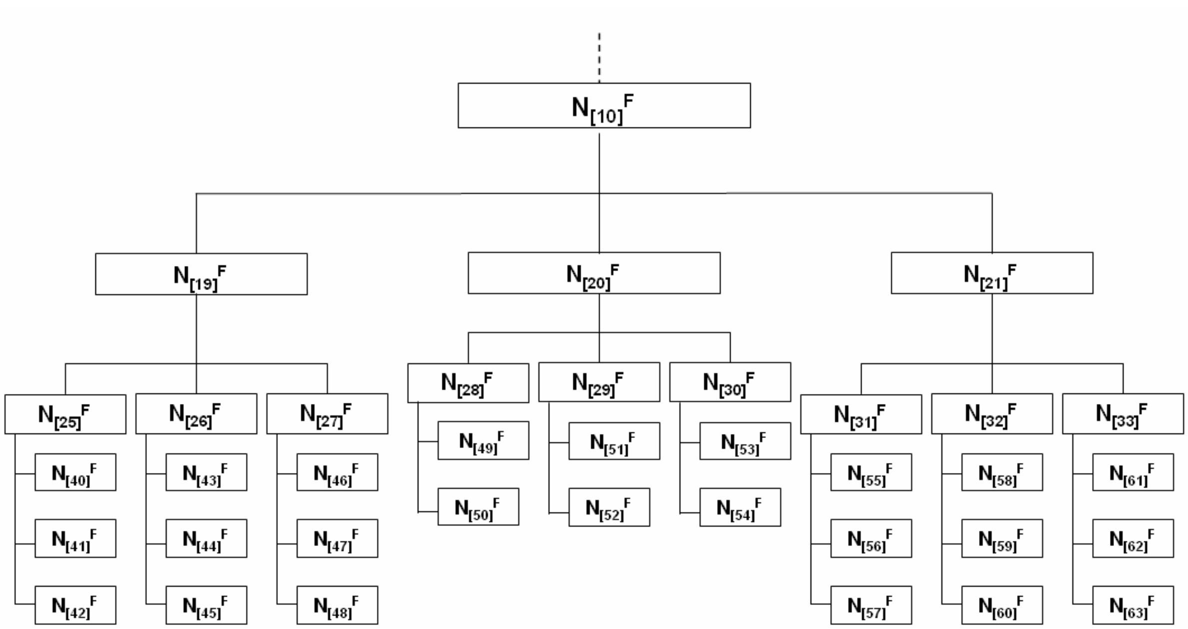

Figure 4-6. State representation of telecommunications decomposition

The telecommunications system subobjective, $O_{1.6}$, is achieved when the following objective end states are achieved.

Table 4-7. Telecommunications objective end states

System	Objective End State
City Phone System	Capable of initiating/receiving international phone calls
Police Comm System	All required radios are operationally fielded
Fire Comm System	All required radios are operationally fielded
City Postal System	Capable of sending/receiving international mail

In addition to telecommunications improvements, the nation's government and coalition officials are also interested in fixing the nation's financial market. The financial market subobjective, $O_{4.1}$, is represented by $N^{F}_{[16]}$. For this scenario, the nation's financial market is divided into developing a commercial banking system, rebuilding the national stock exchange, and restructuring the national debt, based on weekly status reports (CPA, 2004c:1). Swing weighting techniques were used to develop weights for each financial market subobjective. Restructuring the national debt is considered to be 1.3 times as important as each of the remaining two subobjectives. The commercial banking system and national stock exchange are considered equally important. The weights are captured in Figure 4-7.

The commercial banking system uses the same weights, regional decomposition, and city decomposition that are used for the phone system and postal system. Rebuilding the national stock exchange is decomposed into required facilities, trained personnel, and the policies and standards that define the necessary conditions and practices of stock exchange members. The facilities and trained personnel are considered equally important to one another and twice as important as the policies and standards. Restructuring the national debt is decomposed into the debt that is owed to 6 different countries. The weight of each country was determined by dividing the debt owed to a country by the total debt owed to all 6 countries.

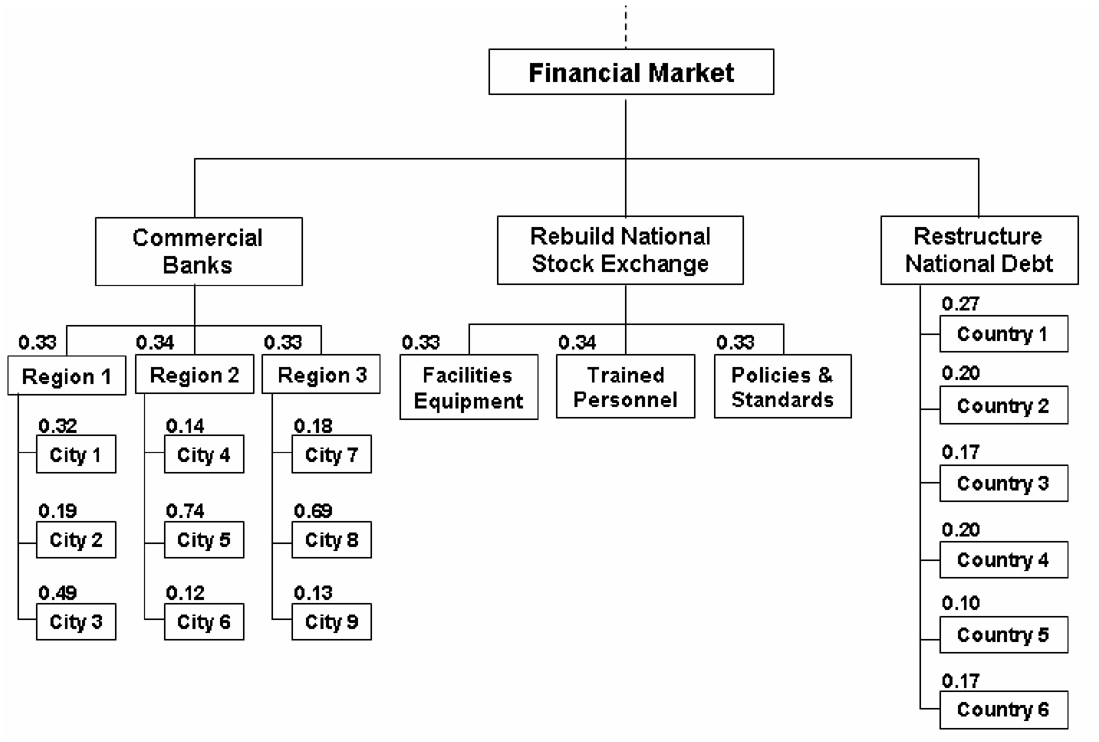

Figure 4-7. Financial market decomposition

Each system's state representation is captured in Figure 4-9. All of the subobjectives are represented by the functional state of a given system with the exception of the subobjectives beneath "Restructuring the national debt." These subobjectives are represented by the behavioral states of 6 different countries. Each behavioral state represents a country's posture toward forgiving a certain amount of debt for each nation.

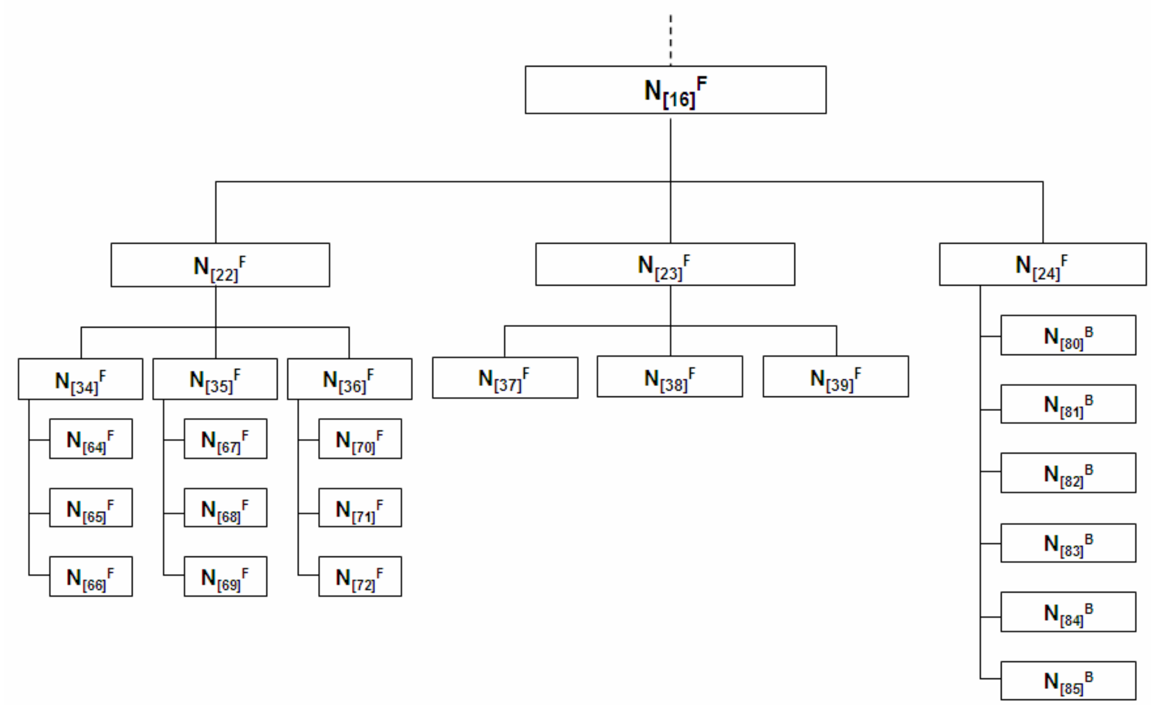

Table 4-8. State representation of financial market decomposition

The financial market subobjective, $O_{4.1}$, is achieved when the following objective end states are achieved.

System	Objective End State
City Banks	Banks are capable of initiating international transactions
Stock Exchange facilities/equipment	Stock exchange facilities and equipment are capable of conducting international trading activities
Stock Exchange Trained Personnel	All required stock exchange personnel are trained
Stock Exchange Policies & Standards	Required policies and standards that define the conditions and practices for stock exchange members
Country Posture	Country is willing to forgive at least 2/3 of the total debt owed to that country

Table 4-9. Financial market objective end states

At this point, all of the objective end states for $O_{1.6}$ and $O_{4.1}$ are identified to meet the needs of the scenario. While it is possible to decompose the different systems to lower levels, it is not necessary for analysis. There is enough system resolution within the current model to distinguish between different resource package combinations.

4.4.2. Value Model

Piecewise linear, single dimensional value functions were developed for each functional or behavioral state that is used to represent the objective end states for $O_{1.6}$ and $O_{4.1}$. Each single dimensional value function is normalized between 0 and 1 and is captured in Appendix A. This section summarizes the possible states for each subobjective's state representation.

Each city's phone system uses the same single dimensional value function. Four states are used to describe the different levels of service for a city's phone system. If a city's phone system is capable of providing citywide service, it scores a value of 0.6. If the city's phone system is capable of providing nationwide phone service, it scores a value of 0.9. If the city's phone system is capable of providing international phone service, it scores full value.

Table 4-10. Functional states and values for a city phone system

State	Description	Value
1	No phone service available in city	0
2	Citywide phone service available in city	0.6
3	Nationwide phone service available in city	0.9
4	International phone service available in city	1

The regional police emergency radio systems and fire emergency radio systems share the same linear value function. The value function has a slope of 1 and is based on the percentage of the required police or fire radios that are operationally fielded. For example, if all of the required police radios are operationally fielded for a given region, full value is received. If 70% of the required radios are operationally fielded for a given region, a value of 0.70 is received.

Each city's postal system shares the same value function. Four states describe the different levels of service for a city's postal system. If a city's postal service is capable of providing citywide postal service, it scores a value of 0.5. If a city's postal service is capable of providing nationwide postal service, it scores a value of 0.95. The ability to provide international postal services scores full value.

Table 4-11. Functional states and values for a city postal system

State	Description	Value
1	No postal service available in city	0
2	Citywide postal service available in city	0.5
3	National postal service available in city	0.95
4	International postal service available in city	1

Each city's commercial banking system uses a common value function based on the same service principles as the phone and postal systems' value functions. The possible states and their corresponding values are captured in Table 4-12.

Table 4-12. Functional states and values for a city banking system

State	Description	Value
1	No banks available in city	0
2	Banks in city capable of citywide transactions	0.4
3	Banks in city capable of nationwide transactions	0.75
4	Banks in city capable of international transactions	1

The national stock exchange's facilities and equipment subobjective is modeled with a piecewise linear value function based on 3 possible functional states. If the stock exchange facilities and equipment are capable of conducting nationwide stock trading, a score of 0.7 is obtained. Full value is obtained when the facilities and equipment are capable of supporting international stock trading.

Table 4-13. Functional states and values for stock exchange facilities and equipment

State	Description	Value
1	No facilities available	0
2	Facilities capable of national trading	0.7
3	Facilities capable of international stock trading	1

The stock exchange's trained personnel subobjective uses a linear value function that is identical to the police and fire communications systems' linear value function. The value function has a slope of 1 and is based on the percentage of required personnel that are trained. The remaining stock exchange subobjective, policies and standards, is a binary value function. If the policies and standards are in place, full value is received. If not, no value is received.

Each country's posture is scored using a unique piecewise linear value functions. It is assumed that the nation has accumulated $150B total debt to the 6 countries. The total debt was randomly partitioned to each country. According to the CPA's weekly status report, an initial goal was reducing Iraq's total debt by 2/3 or more [CPA, January 2004]. Therefore, if a country is willing to forgive 2/3 of the debt it is owed, full value is received for that country's subobjective. The following table summarizes the total debt and 2/3 break point for each country.

Table 4-14. Debt and 2/3 breakpoint for each country

Country	Debt Owed (in $B)	2/3 Breakpoint (in $B)
1	40	27
2	30	20
3	25	17
4	30	20
5	15	10
6	10	7

The weights and single dimensional value functions are combined to form an additive value function. The additive value function serves as the objective function for the mixed integer program described in Section 4.4.4. The remaining campaign objectives (O_2 and O_3) and subobjectives ($O_{1.1}$ through $O_{1.5}$, $O_{2.1}$ and $O_{2.2}$, $O_{3.1}$ through $O_{3.3}$, $O_{4.2}$, and $O_{4.3}$) are assumed to be modeled by functional states that will remain constant throughout the current planning horizon. In other words, resource packages that are used to improve the telecommunications and financial market systems will not result in changes to the remaining objectives and subobjectives.

Even though independence assumptions cannot be guaranteed, the use of an additive value function is justified for two reasons. First, the main objectives and supporting subobjectives are defined in an attempt to preserve independence. For example, it could be argued that the national stock exchange is dependent on City 5's phone system. However, the subobjective is defined and strictly measured in terms of the percentage of required personnel that are trained, the policies and standards, and the status of the facilities and equipment that are <u>unique</u> to stock exchange operations.

Second, independence conditions are in place to ensure that the additive value function does not undervalue or overvalue the different resource package combinations.

Otherwise, the comparisons between alternatives are inconsistent and flawed. In the mixed integer program, the value of direct effects and known indirect and cascading effects are assigned to each resource package for each functional and behavioral state.

For example, the nation's stock exchange is assessed as being dependent on City 5's phone system. Resource packages that are designed to provide nationwide and international phone services in City 5 are assigned a percentage of the total value within the stock exchange facilities and equipment subobjective. The additional value is attributed to the resource packages to account for the value of the indirect effect to the national stock exchange.

4.4.3. Resource Package Alternatives

Seventy two resource package alternatives were developed for the current planning horizon. The national telecommunications system can be improved by any combination of 42 resource package alternatives (11 for phone services, 18 for national emergency services, and 13 for postal services). The financial market can be improved by any combination of 30 resource package alternatives (10 for commercial banks, 3 for the stock exchange, and 17 trade agreement packages for debt reduction). Indirect effects were identified for several resource packages. Indirect effects were assigned using methods described in Section 4.8. The resource package alternatives are captured in Appendix B.

Within this scenario, there are 10 types of resources that are available. **Large construction teams** are required for major projects that include building an international postal service center, regional postal distribution centers, building a nation-wide fiber optic network. **Medium construction teams** are required for jobs that include building city post offices, commercial banks, and installing a satellite gateway system for international calling. **Small construction teams** are required to install telephone exchange switches and cellular phone towers that are used to establish citywide phone services. **Training teams** are required to train phone system, postal system, national stock exchange, and commercial banking system employees. **Radios** are required to field the national emergency system. **Four types of trade agreement packages** are available to influence a country to forgive different amounts of debt ($5B, $7B, $10B, and $20B). A **stock exchange policy team** is required to help the interim government draft its standards and policy documents that are required. An additional resource, **money**, is used in Sections 4.6 and 4.7. Cost estimation methods for each resource package are described in Appendix B.

4.4.4. Mixed Integer Program

The objective function for this scenario is

$$\max \sum_{\forall i} w_{[i]} \cdot V(\Delta N_{[i]}^{F/B})$$

where "F/B" superscript denotes either a functional or behavioral state. The objective function is subject to 10 resource constraints (with slack variables), 42 effects constraints (one constraint for each objective end state), 12 node constraints, and 36 value constraints. The node constraints are needed to prevent more than one trade agreement or regional radio system package from being selected to influence a country's posture or regional radio system.

Each resource package is represented by a binary variable. The slack variables are integer variables. Traditional non-negativity constraints are applied to prevent the slack variables from representing negative quantities.

4.5. Determining the Value of a Resource

The value of a resource is dependent on the number of selected resource packages that require the use of the resource and the total quantity of the resource that is used within the operational plan. The mixed integer program selects the best combination of resource packages to achieve the greatest number of objectives. The resource combinations are bounded by the quantity of available resources.

The value of a resource is computed in an unbounded environment. There are enough available resources to simultaneously achieve all of the telecommunications and financial market subobjectives. The following table summarizes the quantities of each resource type that are available in the scenario.

Table 4-15. Available resources for the scenario

Resource Type	Quantity
Large Construction Teams	19
Medium Construction Teams	70
Small Construction Teams	224
Training Teams	103
Radio Systems	10000
$5B Trade Agreement	5
$7B Trade Agreement	5
$10B Trade Agreement	5
$20B Trade Agreement	4
Stock Exchange Policy Team	1

The integer program selected 49 resource packages to achieve all 42 of the telecommunications and financial market subobjectives. The value of each resource package, in terms of all of the campaign objectives, was calculated by selecting each resource package one at a time within the mixed integer program. The value of each resource package was then divided equally among the different resource types that were required for the given resource package. This step yielded the value of each resource type for a given resource package.

The value of each resource type, in terms of all of the campaign objectives, was then calculated by summing each resource type's values for each resource package. The value of each resource type is shown in Figure 4-8.

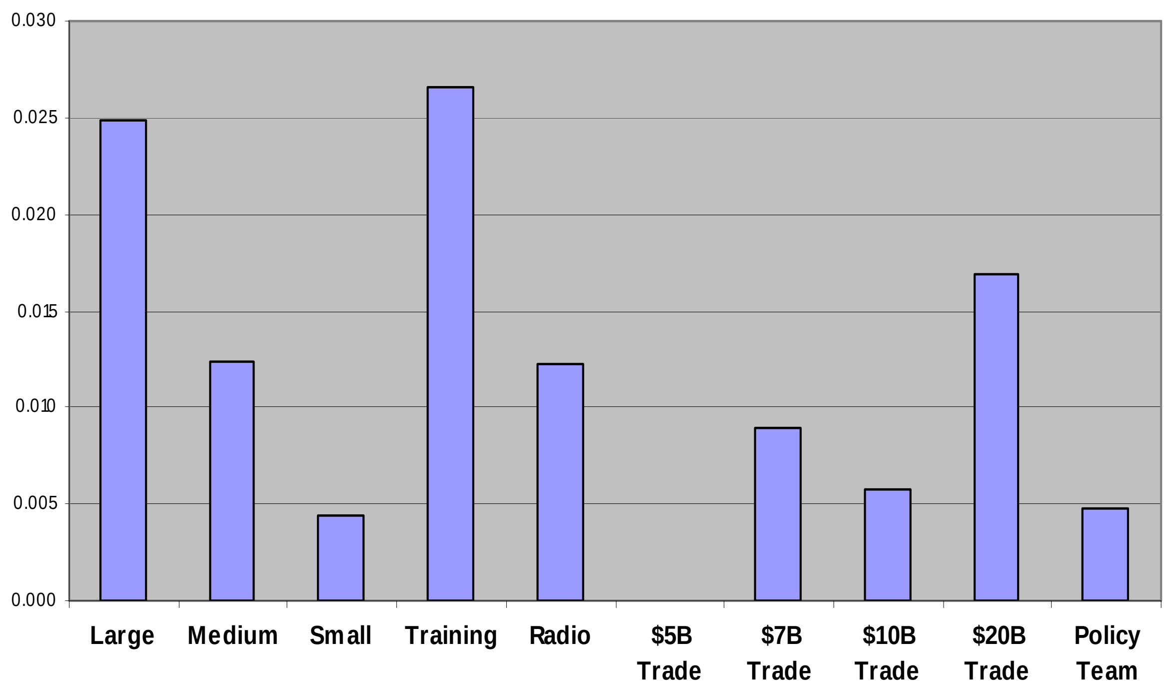

Figure 4-8. Value by resource type

The sum of the resource type values equals 1, as expected. Training teams receive the highest value since they are required to train the stock exchange personnel, commercial bank personnel, phone system personnel, and postal service personnel. The small construction teams receive the smallest value since they are solely focused on establishing citywide phone services for each city. The $5B trade agreements were not selected.

However, the value of a resource is also meaningful when it is expressed at the individual unit level. It allows a commander to determine the relative value of an individual resource when compared to other resources. It also helps a commander prioritize resources in general categories. The value of each individual resource is determined by dividing the value of each resource type by the total quantity of the resource type that are used in the operational plan. The value of each individual resource is captured in Figure 4-9.

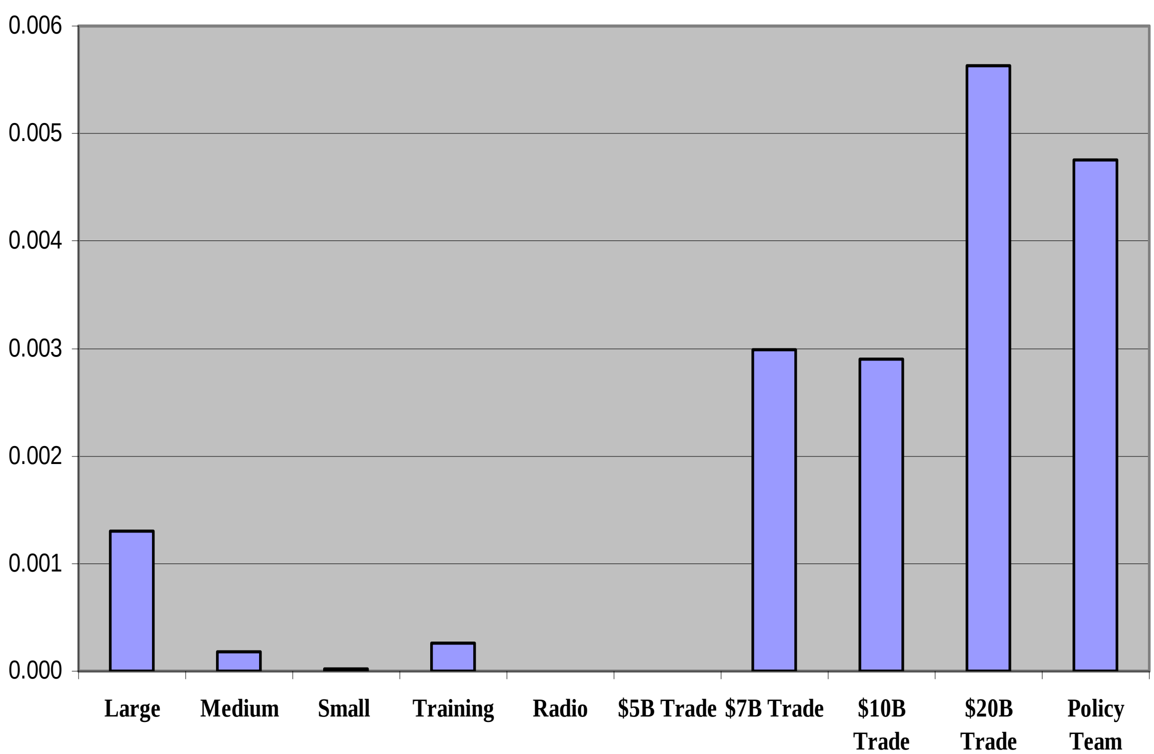

Figure 4-9. Value of an individual resource

The $20B trade agreement and stock exchange policy teams are now the two most valuable resources due to relatively small quantities. On the other hand, the radios, training teams, and construction teams yield small individual values due to the large quantities of each resource that are required. A commander can use Figure 4-9 to determine different categories of prioritized resources at the individual resource level.

Table 4-16. Prioritization by individual resource type

Resource Type	Priority I ($V > 0.003$)	Priority II ($0.001 < V \le 0.003$)	Priority III ($0 < V \le 0.001$)
Large Construction		X	
Medium Construction			X
Small Construction			X
Training Teams			X
Radio Systems			X
$5B Trade Agreement			X
$7B Trade Agreement		X	
$10B Trade Agreement		X	
$20B Trade Agreement	X		
Stock Exchange Policy Team	X		

In Section 4.6, a budgetary constraint is added to the integer program. Resource packages are selected based on the available budget. Sensitivity analysis is performed to see how the value of an individual resource changes as the available budget is changed.

4.6. Sensitivity Analysis

The available budget ranged from $1.2B to $0 in increments of $100M. Cost estimates were developed for the different construction projects and training requirements and are captured in Appendix B. The quantities of the different trade agreements were held at a constant level throughout the exercise to prevent the integer program from trading a $5B trade agreement to fund all of the remaining resource packages to achieve all of the objectives. Resource values were recalculated for each available budget.

Figure 4-10 shows the change in resource type value with respect to the available budget. The trade agreement resource packages are not included in the graph since they remain constant.

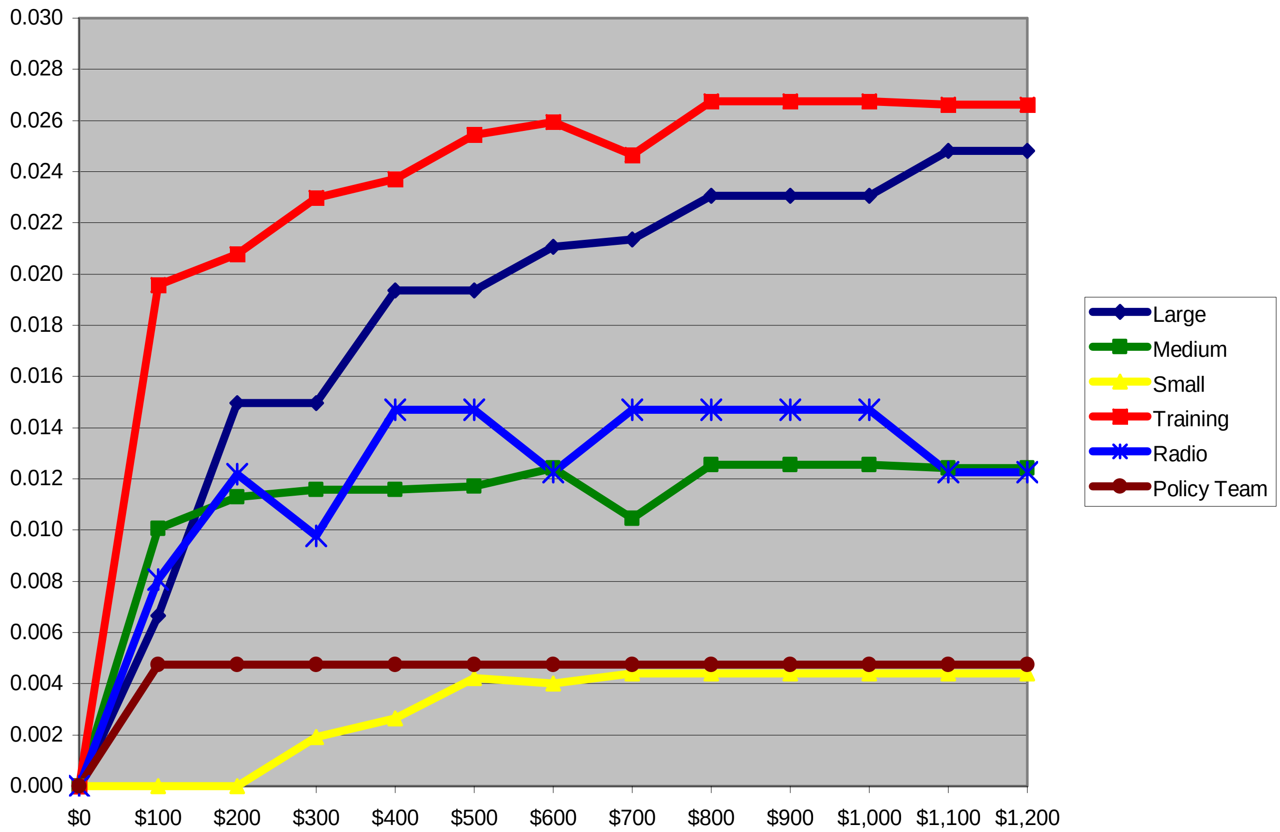

Figure 4-10. Resource type value per available budget (in $M)

The small construction teams are consistently ranked as the least valued resource type since the teams only focus on establishing citywide phone services. In contrast, training teams are consistently ranked as the most valued resource type since they are used to achieve financial market and telecommunications subobjectives. Also, the training teams and medium construction teams work together to establish citywide banking services and citywide postal services. Therefore, the values for the two resource types are positively correlated. The training teams also work with the small construction teams to establish citywide phone services. Again, the values for the two resource types are also positively correlated.

Crossovers indicate a change in order for the different resource types. The first crossover occurs between $100M and $200M. Three large construction teams are funded to install a nationwide fiber optic network that facilitates nationwide bank transactions. The large construction teams earn value for each city's banking system, causing it to become the third most important resource type. Two regional police communications systems are fully operational, causing radios to become the fourth most important resource. The remaining crossovers occur between the medium construction teams and the radio systems. Order transitions between these resource types are a function of the weights of particular city banking systems, city postal systems, and regional police and fire communications systems.

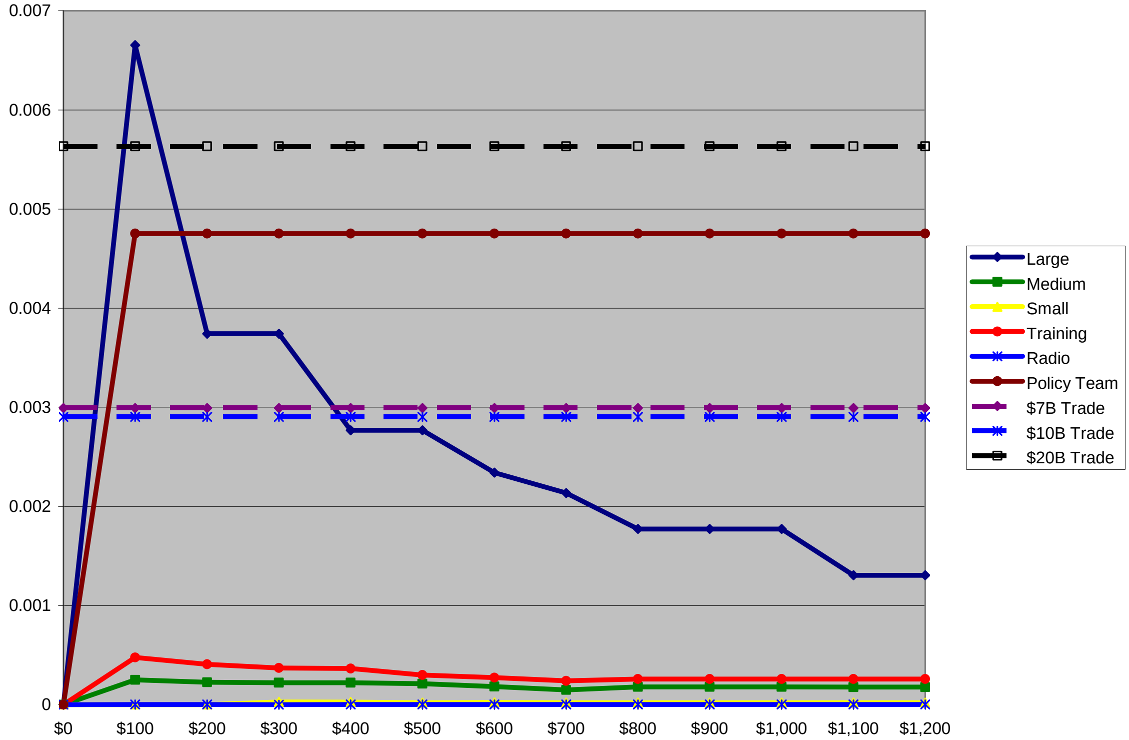

Figure 4-11. Individual resource value by available budget in ($M)

The value of a large construction team is the most sensitive value to changes in available budget, as depicted in Figure 4-11. At $100M, a single construction team is funded to build the national stock exchange facilities. However, at $200M, three large construction teams are used to build the bank system's nationwide fiber optic network. The individual resource value for a large construction team decreases significantly since the value of the resource type is now being divided by 4.

The individual values of the training teams, medium teams, small teams, and radios are very small due to the large quantities of each resource type that are used. Medium construction teams and training teams exhibit the same positive correlation that was identified in Figure 4-10. Small construction teams and training teams also exhibit positive correlation for similar reasons. The small construction teams and handheld radios are used in great quantities. At the individual resource level, their contributions earn miniscule amounts of value.

4.7. Identifying Competing Objectives

Objectives exhibit a competitive relationship with other objectives if they require the simultaneous use of the same type of limited resources. In this section, the budget constraint is used to generate a scenario with limited resources.

Table 4-17. Resource quantities

Large	Medium	Small	Training	Radios
13	70	224	103	10000

If the financial market and telecommunications subobjectives are both achieved, a total value of 0.12 is earned. Therefore, if the scenario's resources cannot achieve both subobjectives, then there are limited resources. Competition may exist between lower level subobjectives.

The available resources in scenario 1 earned a value of 0.118. For scenario 1, there are insufficient resources. The slack variables did not identify any excess resources. Therefore, each resource constraint is considered a binding resource constraint.

In this scenario, the financial market subobjective was achieved. However, the telecommunications system did not achieve full value. Examination at the next lowest tier revealed the following information.

Table 4-18. Values for 3rd tier subobjectives

Subobjective	Description	Value
$O_{1.6.1}$	Phone System	1
$O_{1.6.2}$	National Emergency Service	1
$O_{1.6.3}$	Postal System	0.847
$O_{4.1.1}$	Commercial Banking System	1
$O_{4.1.2}$	National Stock Exchange	1
$O_{4.1.3}$	Restructure National Debt	1

The postal system subobjectives showed that Region 2 postal services were not fully functional.

Table 4-19. Values for 4th tier subobjectives

Subobjective	Description	Value
$O_{1.6.3.1}$	Region 1 Postal System	1
$O_{1.6.3.2}$	Region 2 Postal System	0.55
$O_{1.6.3.3}$	Region 3 Postal System	1

The 3 city postal systems within Region 2, including the capital city, each achieved a value of 0.55.

Table 4-20. Values for the bottom tier subobjectives

Subobjective	Description	Value
$O_{1.6.3.2.1}$	City 4 Postal System	1
$O_{1.6.3.2.2}$	City 5 Postal System (Capital)	0.55
$O_{1.6.3.2.3}$	City 6 Postal System	1

Each city's postal system is capable of providing citywide postal services (scoring a value of 0.5). Additionally, the international postal service center was constructed to make international shipping possible for all cities (scoring a value of 0.05). However, Region 2's postal distribution centers were not constructed.

Resource package $R_{13(11)}$ enables the construction of Region 2's postal distribution centers. There are 6 postal distribution centers in Region 2 based on total population of the three cities. According to the resource constraints, 6 large construction teams are required to build the distribution centers. At this point, the large construction team resource constraint is identified as the binding constraint. The remaining resources are nonbinding resource constraints.

Large construction teams are used to build the national stock exchange, to install the national fiber optic networks for nationwide phone communications and bank transactions, and to build regional postal distribution centers. The competing objectives in this scenario are listed in Table 4-21.

Table 4-21. Competing objectives

Subobjective	Description	Value
$O_{1.6.1}$	**Phone System**	1
$O_{1.6.3}$	**Postal System**	0.847
$O_{4.1.1}$	**Commercial Banking System**	1
$O_{4.1.2}$	**National Stock Exchange**	1

Different binding constraints can potentially identify different competing objectives within the same scenario. For example, small construction teams only support citywide banking services, citywide postal services, and international calling services. Therefore, in the case where small construction teams are identified as a binding resource, $O_{4.1.2}$ would not be listed as a competing objective for small construction team resources. Therefore, the techniques used in this section should be implemented for each binding resource constraint.

This process works very well. The integer program is designed to show each subobjective's value at each level of aggregation (e.g., each tier of the objective hierarchy). It only took a matter of seconds to identify the subobjective that was not being fully achieved and the resource packages that were designed to achieve the subobjective.

Slack variables provided limited utility. However, in other situations, the slack variables may be used to identify resources that can be held in reserve or used for other purposes. Therefore, it is left to the reader to determine whether or not slack variables are important enough to include in the integer program based on personal preferences.

4.8. Conflicting Objectives

Conflicting objectives exist when the achievement of one objective leads to a reduction in the degree of achievement of a second objective. The stability operations scenario that is used in this chapter does not provide a good example for illustrating conflicting objectives.

The one exception is found in the relationship between the financial market and human resources subobjectives ($O_{4.1}$ and $O_{4.2}$). At first, it appears as though these subobjectives are not in conflict with each other. However, further inspection yields the following results.

Restructuring the national debt is a subobjective that supports $O_{4.1}$. Trade agreements are used to influence a given country to forgive the nation's debt. If the trade agreements involve an exchange of goods or services, there is no conflict between objectives. However, if trade agreements allow a foreign country to operate businesses within the nation's borders, the potential exists for conflict between restructuring the national debt and developing a long term human resources strategy.

For example, Country 6 forgives $7B of the debt that is owed. In exchange, the new government allows Country 6 to establish commercial banks in 5 of the major cities. The owners of the commercial banks transfer foreign employees from Country 6 to operate the banks. The improvement in restructuring the national debt leads to a reduction in the number of employed citizens within the nation. If the human resources subobjective is written in terms of increasing employment national employment opportunities, a conflicting relationship exists between $O_{4.1}$ and $O_{4.2}$.

In Section 4.4.2, an additive value function was selected under the assumption that the value of any indirect effects and cascading effects would be assigned to the appropriate resource packages. This assumption was required to justify the use of an additive value function when independence conditions could not be guaranteed. The following example is used to show how indirect effects were assigned to $R_{11(11)}$, a resource package that is used to create a satellite gateway system that will provide international phone services.

Resource packages are scrutinized to identify any indirect effects or cascading effects resulting from the actions enabled by a given resource package. In Section 4.4.2, it was postulated that the national stock exchange's functional state depended on City 5's phone system. The following resource packages are reviewed to see if there are any indirect effects or cascading effects to the financial market subobjectives.

Table 4-22. Resource packages

Resource Package	Description
R_{115}	Establish Citywide Phone Service in City 5
$R_{11(10)}$	Establish fiber optic network to provide nationwide calling in each city
$R_{11(11)}$	Establish satellite gateway service for international calling in each city

The financial market is divided into three supporting subobjectives that represent the commercial banking system (modeled as $N^F_{[22]}$), the national stock exchange (modeled as $N^F_{[23]}$), and the national debt (modeled as $N^F_{[24]}$). Each resource package is reviewed to see if it impacts the supporting subobjectives.

Table 4-23. Second tier interaction table

Resource Package	$O_{4.1}$		
	$N^F_{[22]}$	$N^F_{[23]}$	$N^F_{[24]}$
R_{115}	?	?	N/A
$R_{11(10)}$	?	?	N/A
$R_{11(11)}$	?	?	N/A

The resource packages do not impact restructuring the national debt. However, at this level of aggregation, there is insufficient information to identify any indirect effects or cascading effects. Therefore, the commercial banking system and national stock exchange are decomposed further into the regional banking systems $(N^F_{[34]}, N^F_{[35]}, N^F_{[36]})$ and the national stock exchange's facilities and equipment, trained personnel, and standards and policies $(N^F_{[37]}, N^F_{[38]}, N^F_{[39]})$.

Table 4-24. Third tier interaction table

Resource Package	$O_{4.1.1}$			$O_{4.1.2}$		
	$N^F_{[34]}$	$N^F_{[35]}$	$N^F_{[36]}$	$N^F_{[37]}$	$N^F_{[38]}$	$N^F_{[39]}$
R_{115}	N/A	?	N/A	?	N/A	N/A
$R_{11(10)}$	?	?	?	?	N/A	N/A
$R_{11(11)}$	?	?	?	?	N/A	N/A

R_{115} does not impact the banking services within Regions 1 and 3. However, it is unclear if the commercial banking networks connect to the phone system's national fiber optic network or the international satellite gateway. At this level of aggregation, it is also not known if the national stock exchange's facilities and equipment depend on the phone system. Fourth tier comparisons are required.

Each region's commercial banking system is divided into the city banking systems that are within the region. The national stock exchange facilities and equipment requires the development of fourth tier state representations. The following state representations are used for each subobjective.

Table 4-25. State representations for city banks and stock exchange equipment

Description	State Representations
City commercial banking systems in Region 1	$N^F_{[64]}$, $N^F_{[65]}$, $N^F_{[66]}$
City commercial banking systems in Region 2	$N^F_{[67]}$, $N^F_{[68]}$, $N^F_{[69]}$
City commercial banking systems in Region 3	$N^F_{[70]}$, $N^F_{[71]}$, $N^F_{[72]}$
National stock exchange computer network	$N^F_{[73]}$
National stock exchange electrical system	$N^F_{[74]}$

The different state representations are used to create a new interaction table. The interaction table is divided into two separate tables due to space limitations.

Table 4-26. Lowest level interaction table--Part 1

Resource Package	$O_{4.1.1.1}$			$O_{4.1.1.2}$		
	$N^{F}_{[64]}$	$N^{F}_{[65]}$	$N^{F}_{[66]}$	$N^{F}_{[67]}$	$N^{F}_{[68]}$	$N^{F}_{[69]}$
R_{115}	N/A	N/A	N/A	N/A	N/A	N/A
$R_{11(10)}$	N/A	N/A	N/A	N/A	N/A	N/A
$R_{11(11)}$	+	+	+	+	+	+

Table 4-27. Lowest level interaction table--Part 2

Resource Package	$O_{4.1.1.3}$			$O_{4.1.2.1}$	
	$N^{F}_{[70]}$	$N^{F}_{[71]}$	$N^{F}_{[72]}$	$N^{F}_{[73]}$	$N^{F}_{[74]}$
R_{115}	N/A	N/A	N/A	N/A	N/A
$R_{11(10)}$	N/A	N/A	N/A	N/A	N/A
$R_{11(11)}$	+	+	+	+	N/A

Looking at each city's banking system, it is determined that the commercial bank's national fiber optic network is a secure system that is separate from the phone system's national fiber optic network. However, the bank system's fiber optic network and the stock exchange's computer network are planned to be connected to the international satellite gateway to conduct international transactions. Therefore, it is necessary to assign additional value to $R_{11(11)}$ to account for the indirect effects to the nation's stock exchange facilities and each city's banking system.

Despite not having any conflicting objectives, the scenario provided an opportunity to prove that the relationships between objectives could be identified using the method described in Section 3.5. It is recommended that this method is used when constructing resource packages. In some cases, the method will identify a conflicting relationship between objectives that is caused by the actions that are enabled by a given resource package. In other cases, as shown in this section, indirect effects or cascading effects are discovered. The use of interaction tables at different levels of aggregation provides a logical process for decomposing the system to discover the relationships between objectives.

4.9. Summary

The results of the analysis suggest that the methodology described in Chapter 3 can be used to determine the value of a resource within the context of campaign objectives. A commander can use this information to prioritize his resources into several categories based on resource values at the individual resource level.

Competing objectives were quickly identified by starting at the highest level of the objectives hierarchy and working down to the individual subobjective that was not achieving full value. The resource packages that were associated with the subobjective were then used to identify the binding constraints. Slack variables were not that useful. However, in other situations, they may be able to identify resources that can be held in reserve or used for other purposes.

Conflicting objectives were not identified in this scenario. However, interaction tables were used at different levels of aggregation to identify several indirect effects associated with the installation of the international satellite gateway system. It is recommended that this process be used when developing resource packages during course of action development.

5. Summary and Recommendations

5.1. Overview

This chapter summarizes the operational contributions of this thesis, key observations regarding the use of the techniques within this research, and recommendations for future research. Section 5.2 identifies the contributions of this research to effects-based operational concepts. Section 5.3 captures the key observations from using the methodologies that are described in Chapter 3. Section 5.4 identifies recommended areas for future research. Section 5.5 summarizes the final conclusions.

5.2. Contributions of this Research

This research translated doctrinal, effects-based operational concepts into actionable processes that are applicable across the spectrum of military operations. Using the methodologies described in Chapter 3, operational planners can calculate the value of a resource within the context of campaign objectives, identify competing objectives in the presence of limited resources, and identify conflicting objectives for an operational campaign. From a doctrinal perspective, the research also introduces the concept of the EBO prism to link the strategic, operational and tactical levels of war in a coherent fashion.

First, the research offers a new way to express resource value in terms of a campaign’s objectives. The desired end state and objectives hierarchy of an operational campaign are translated into objective end states. This state representation of the objectives hierarchy is used to develop a multiple objective value function that measures the value of an effect or set of effects on adversary systems. By linking resources to the effects they produce, resource value is calculated and expressed in terms of the campaign's objectives. Using this information, the commander can prioritize his or her available resources and make improved resource allocation decisions.

Second, the research offers a systematic method for identifying competing objectives within the context of an existing operational plan. An integer program is used to select resource package combinations that achieved the maximum number of objectives within the bounds of available resources. If an objective is not achieved, the planner identifies the resource packages that were not selected to determine the binding resource constraints. Objectives that are associated with the binding resource constraint are said to compete with the unachieved objective for the limited resource. By identifying competing objectives, a commander is able to make more informed resource allocation decisions.

Third, the research creates a quick, systematic method for identifying conflicting objectives. The process is also used to identify indirect or cascading effects that are enabled by a selected set of resources. Using interaction tables, resource packages that are intended to achieve a given objective are compared against the remaining campaign objectives. Comparisons start at the highest level of aggregation (i.e., the top of the objectives hierarchy) and continue to successively lower levels of aggregation until all indirect effects, cascading effects, and conflicting objectives are identified. With this additional information, the commander gains a better understanding of the relationship between objectives. Additionally, planners can use the information to generate new actions and their corresponding resource packages to minimize the level of conflict between objectives.

Lastly, the research introduces the concept of the EBO prism to coherently link the strategic, operational, and tactical levels of war. The EBO prism is a powerful mental model to describe how each participant's objectives, perceptions, and access to information alters his or her view of the true system of systems, the operational environment, and the effects that are produced. The prism also provides a way to describe how the effects of actions can be simultaneously viewed at the strategic, operational, and tactical levels of war.

5.3. Key Observations

Aggregation is a powerful tool to handle the state and node explosion that is often associated with modeling a system of systems. In this thesis, aggregation is used to model a given system to the fidelity that is required to measure the value of a resource, identify competing objectives, and identify campaign objectives. In Chapter 3, aggregation is also used to express the physical, functional, and behavioral states of a given node with the minimum number of possible states. The research indicates that selective aggregation should be used to prevent a system model from becoming unmanageable.

Second, the process for identifying conflicting objectives should also be used during resource package development to identify indirect and cascading effects. Originally, the process was only intended for the identification of conflicting objectives. However, while creating resource packages for the nation-building example, the process also proved to be a quick and easy way to identify indirect and cascading effects in a systematic fashion.

Third, the integer program is useful for other applications not described in Chapters 3 and 4. The integer program is robust enough to handle resource allocation between single or multiple operational campaigns. Combatant commands with global responsibilities, such as US Strategic Command, can use a similar integer program to apportion satellite communications bandwidth across regional combatant commands. Also, the value of each resource package can be calculated. By understanding the value of each resource package, analysts can assess the impacts of diverting resources from their original mission.

5.4. Recommendations for Future Research

There are three recommendations for future research. First, the research is based on the assumption that effects are produced with certainty. Follow-on research should focus on methods to relax this assumption to incorporate uncertainty in the model. For example, probabilities could be associated with the effects that may be generated by a given resource package. Utility theory could then be used to express the utility of a resource within the context of campaign objectives.

Second, the methodology applies to a single planning horizon. This assumption limits the model's ability to represent the temporal nature of effects. Additional research efforts should focus on methods to apply this methodology across multiple planning horizons (e.g., adding another index to the methodologies described in Chapters 3 and 4)

Third, the methods identified in this research should be implemented in an upcoming combatant command-level exercise. In addition to assessing the effectiveness of the methods in a simulated operational environment, the lessons learned could be used to improve the methods or generate other methods. If the methods prove effective in the simulated operational environment, they should be incorporated into existing effects-based planning doctrine.

5.5. Summary

The methods described in this thesis translate doctrinal effects-based operational concepts into actionable processes across the spectrum of military operations. The EBO prism provides the mental construct to coherently link efforts across strategic, operational, and tactical levels. Planners can use the methodologies in this thesis to identify competing objectives, conflicting objectives, and assess the value of a resource in the context of campaign objectives to improve a commander's ability to allocate limited resources.

Appendix A. Single Dimensional Value Functions

This appendix captures the single dimensional value functions for the nation-building example in Chapter 4. Each single dimensional value function corresponds to a subobjective or group of subobjectives within the nation-building campaign's objective hierarchy. All value functions are monotonically increasing functions and are normalized between 0 and 1.

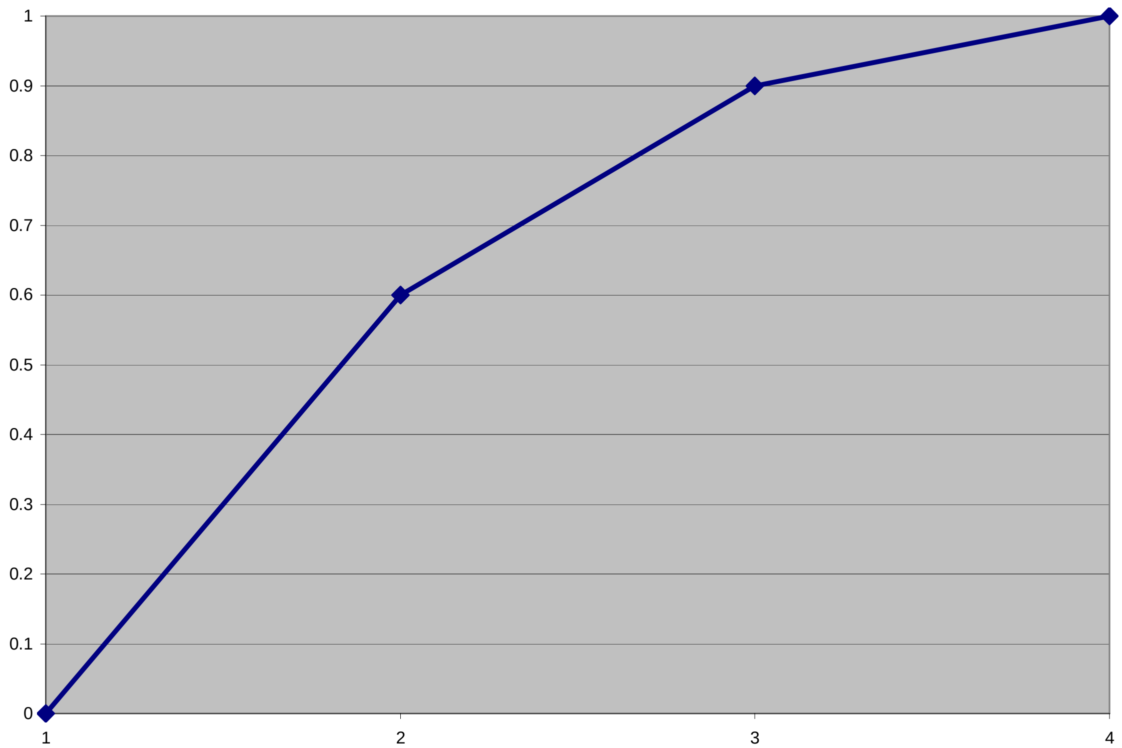

Figure A-1. City phone system's value function

The value of a city's current functional state is assessed using a piecewise linear value function. Citywide phone service is considered twice as important as establishing nationwide phone service and 6 times as important as international phone service based on the frequency with which the author makes each type of phone call on a monthly basis. The corresponding values in Table A-1 reflect these preference statements.

Table A-1. City phone system's functional states and values

State	Description	Value
1	No phone service available in city	0
2	Citywide phone service available in city	0.6
3	Nationwide phone service available in city	0.9
4	International phone service available in city	1

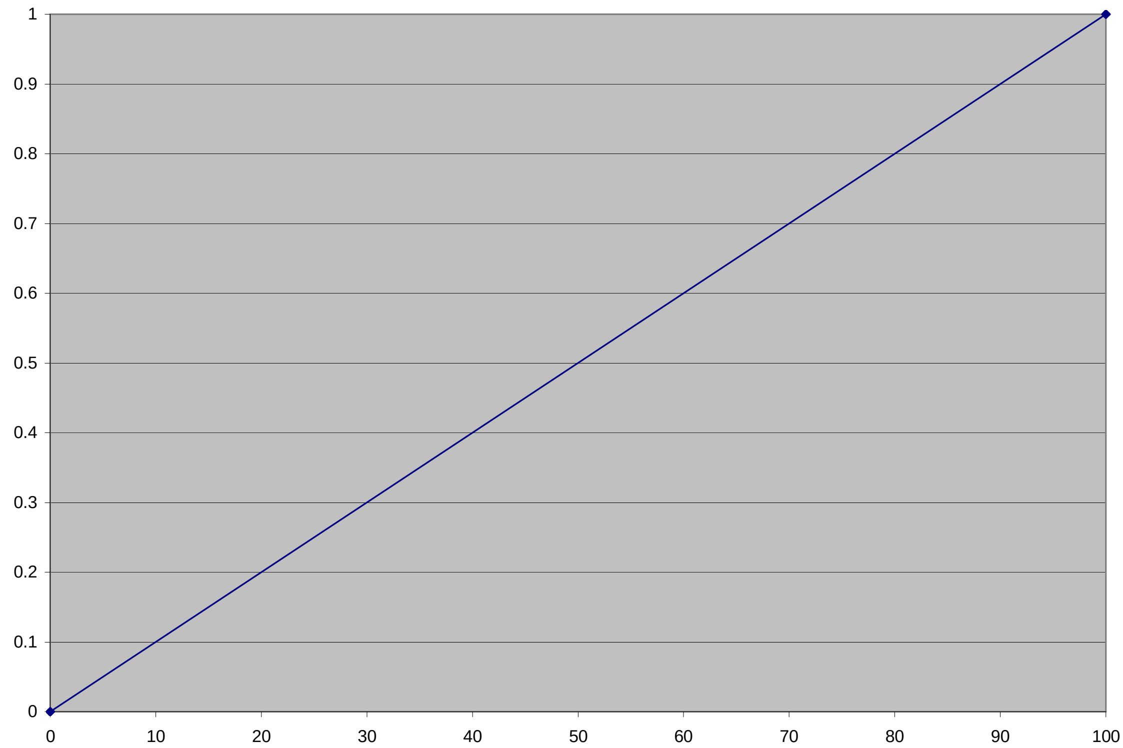

Figure A-2. Regional police/fire emergency radio system's value function

The value of a region's police and fire emergency radio system is assessed using the same value function. The linear value function has a slope of 1. The x axis represents the percentage of required radio systems that are operationally fielded for a regional police or fire emergency radio system.

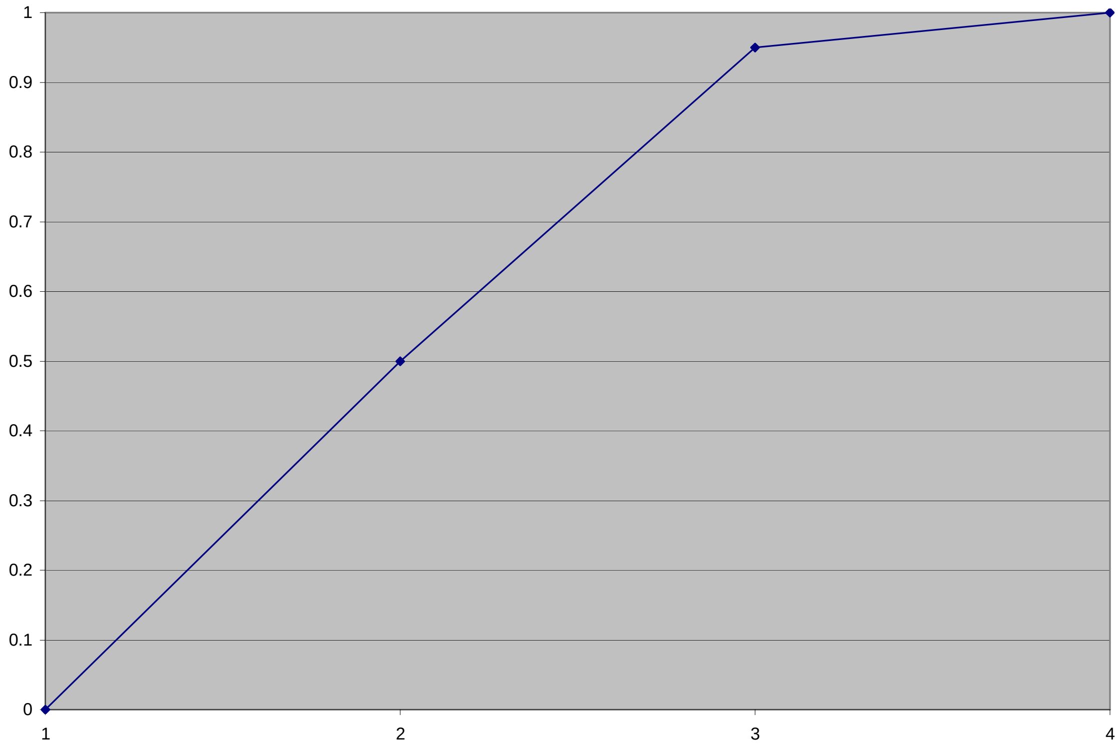

Figure A-3. City postal system's value function

The value of a city's postal system's functional state is assessed using a piecewise linear value function. Citywide postal service is considered 10 times as important as international postal service. National service is considered 9 times as important as international postal service. The preference statements are expressed in terms of a local citizen, not in terms of businesses. The corresponding values in Table A-2 reflect these preference statements

Table A-2. City postal system's functional states and value functions

State	Description	Value
1	No postal service available in city	0
2	Citywide postal service available in city	0.5
3	National postal service available in city	0.95
4	International postal service available in city	1

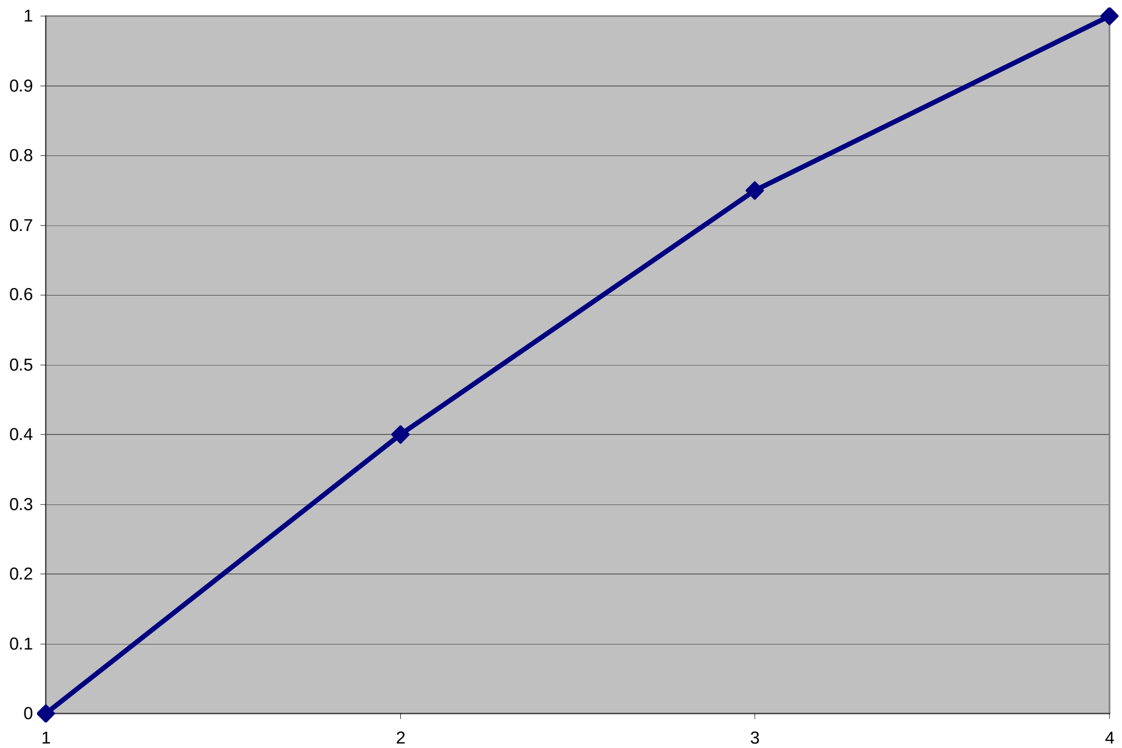

Figure A-4. City banking system's value function

The value of a city banking system's functional state is assessed using a piecewise linear value function. Citywide banking services are 1.6 times more important than international banking services. Nationwide banking services are considered 1.4 times more important than international banking services. The preference statements are written from the perspective of a local citizen.

Table A-3. City banking system's functional states and values

State	Description	Value
1	No banks available in city	0
2	Banks in city capable of citywide transactions	0.4
3	Banks in city capable of nationwide transactions	0.75
4	Banks in city capable of international transactions	1

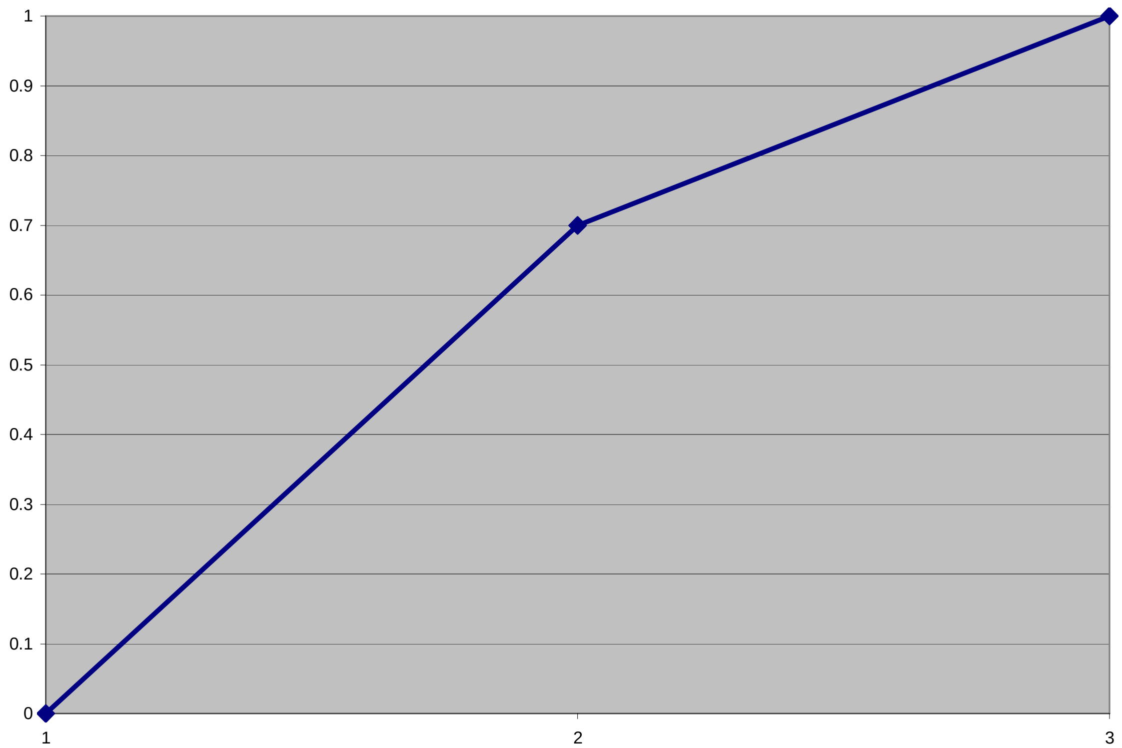

Figure A-5. Stock exchange facilities & equipment value function

The value of the functional state of the stock exchange's facilities and equipment is assessed with a piecewise linear value function. Nationwide trading is considered 2.3 times more important than international trading.

Table A-4. Stock exchange facilities and equipment functional states and values

State	Description	Value
1	No facilities available	0
2	Facilities capable of national trading	0.7
3	Facilities capable of international stock trading	1

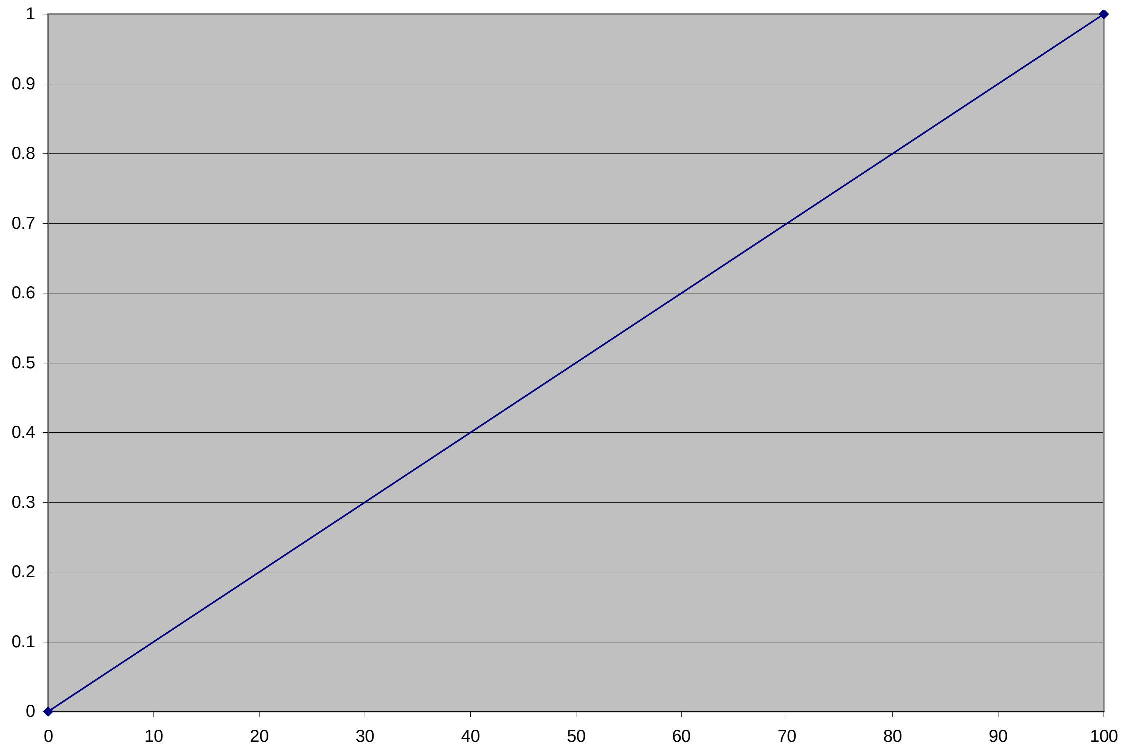

Figure A-6. Trained stock exchange personnel value function

The value of trained stock exchange personnel is assessed with a linear value function that has a slope of 1. The x axis represents the percentage of required stock exchange personnel that are trained.

The value of stock exchange policies and standards is assessed using a binary value function. If policies and standards are in place, full value is earned. Otherwise, no value is earned.

Table A-5. Stock exchange policies and standards value function

State	Description	Value
1	Policies and Standards **are not in place** to govern admittance into the Stock Exchange	0
2	Policies and Standards **are in place** to govern admittance into the Stock Exchange	1

The value of the amount of the nation's debt that a country is willing to forgive is assessed using a piecewise linear value function. Full value is achieved if a country forgives at least two-thirds of the nation's debt. A value function for each country is included.

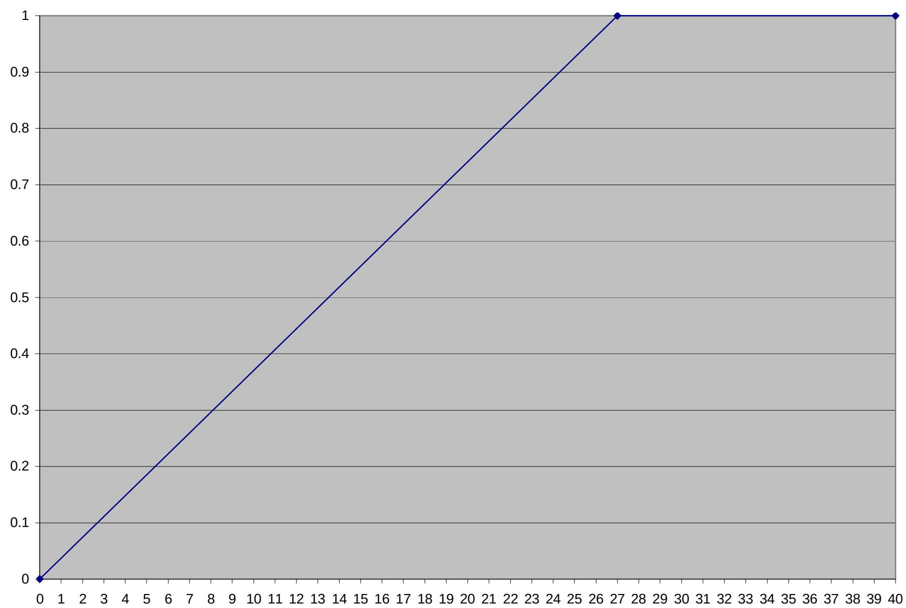

Figure A-7. Value function for debt forgiven by Country 1 (in $B)

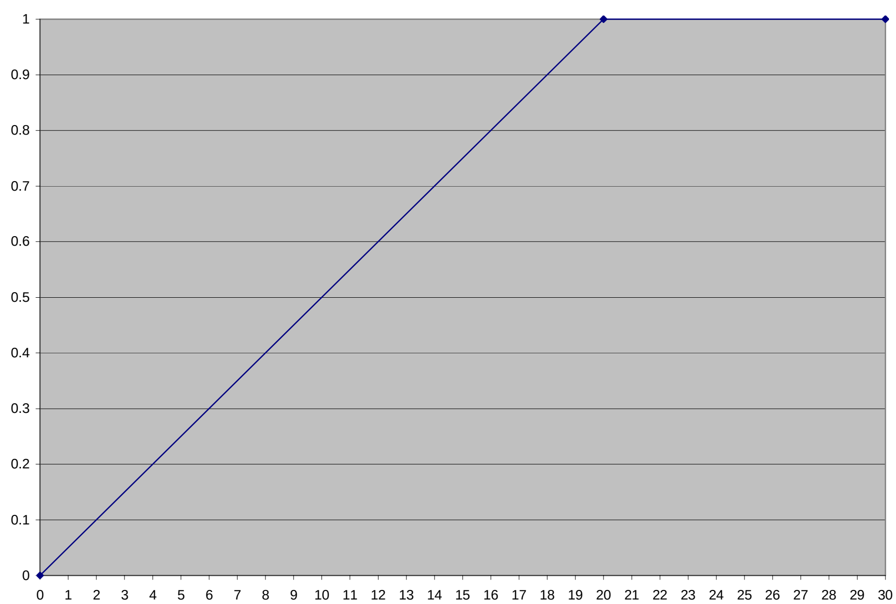

Figure A-8. Value function for debt forgiven by Country 2 (in $B)

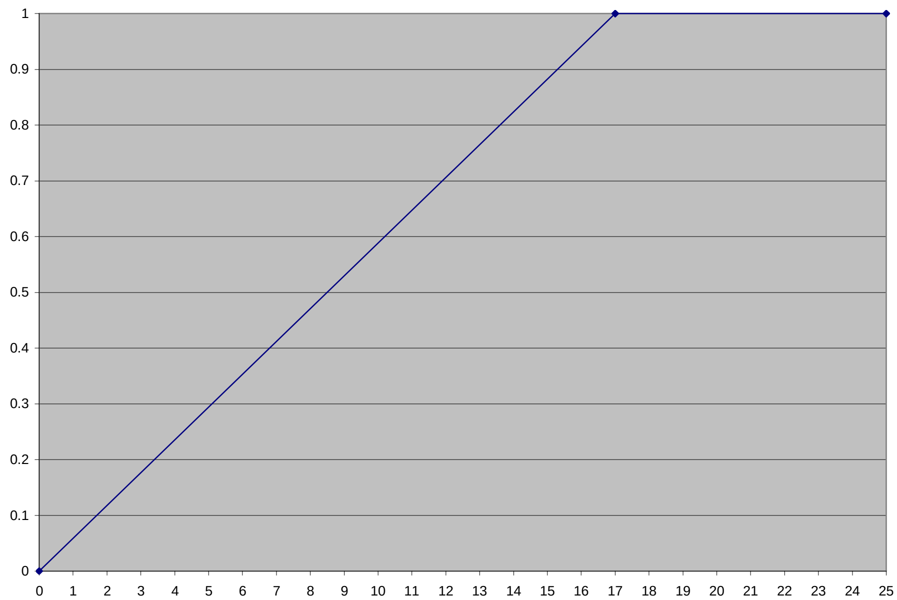

Figure A-9. Debt forgiven by Country 3 value function (in $B)

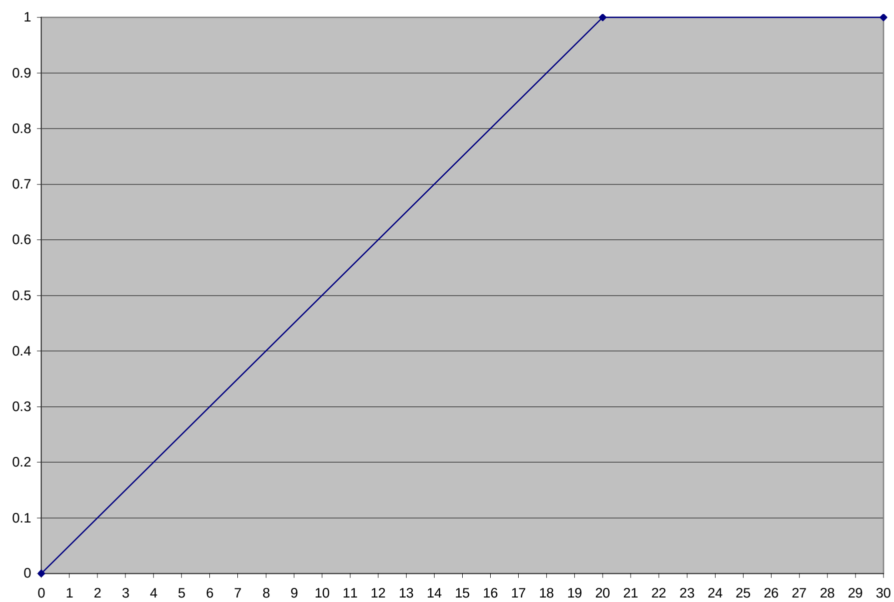

Figure A-10. Debt forgiven by Country 4 value function (in $B)

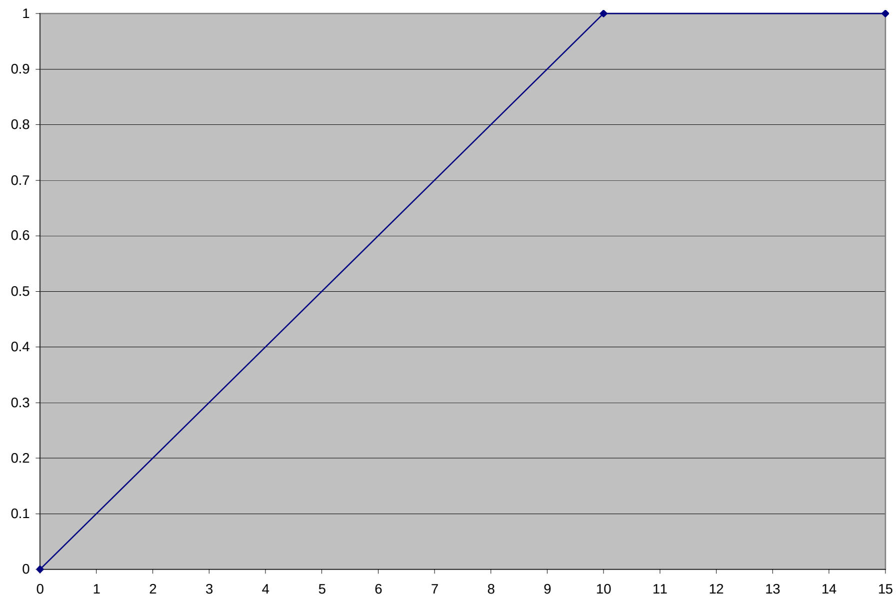

Figure A-11. Debt forgiven by Country 5 value function (in $B)

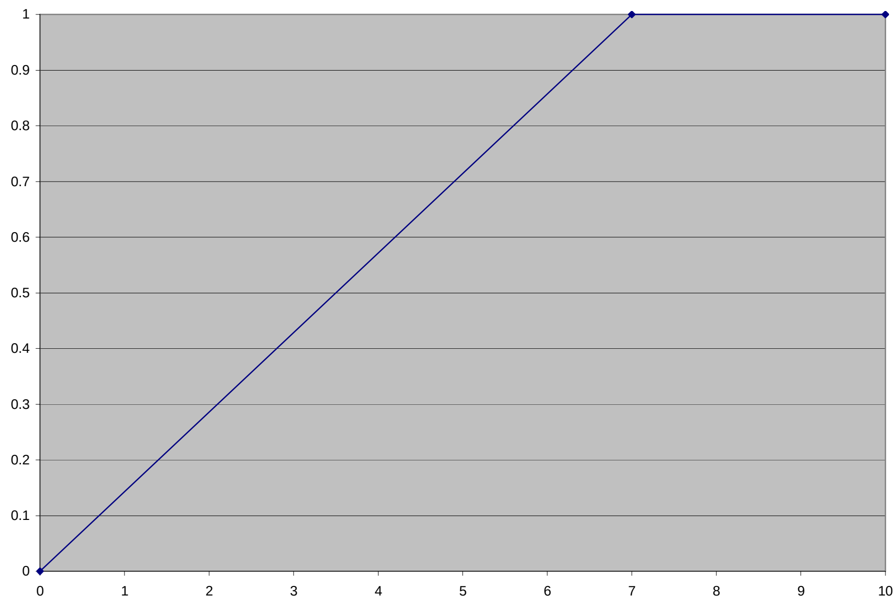

Figure A-12. Debt forgiven by Country 6 value function (in $B)

Appendix B. Resource Package Generation

There are 72 total resource packages that are included in the nation-building scenario. A total of 42 different resource packages designed to improve the national telecommunications system. Nine of the resource packages are designed to establish citywide phone services in each city. Small construction teams and training teams are required to establish citywide phone services.

Table B-1. Resource packages to improve phone systems

Resource Package	Description	Small Teams	Training Teams
$\mathbf{R_{111}}$	**Establish Citywide Phone Service in City 1**	18	2
$\mathbf{R_{112}}$	**Establish Citywide Phone Service in City 2**	10	1
$\mathbf{R_{113}}$	**Establish Citywide Phone Service in City 3**	27	3
$\mathbf{R_{114}}$	**Establish Citywide Phone Service in City 4**	21	3
$\mathbf{R_{115}}$	**Establish Citywide Phone Service in City 5**	78	13
$\mathbf{R_{116}}$	**Establish Citywide Phone Service in City 6**	17	2
$\mathbf{R_{117}}$	**Establish Citywide Phone Service in City 7**	11	1
$\mathbf{R_{118}}$	**Establish Citywide Phone Service in City 8**	34	5
$\mathbf{R_{119}}$	**Establish Citywide Phone Service in City 9**	8	1

The resource requirements for each city were derived in the following manner. Baghdad has 38 operational telephone switches (USAID, 2005). It was assumed that there are a comparable number of antenna towers (40 towers). Therefore, 78 total switches and towers were required for City 5. The quantities of telephone switches and antenna towers for the remaining 8 cities were derived using the ratio between a given city’s population and City 5’s population. The number of training teams was also derived based on population ratios using an estimate of 13 required training teams for City 5.

Two remaining resource packages are also designed to improve the nation's phone services. A nationwide fiber optic network can be built using 3 large construction teams to establish nationwide phone connectivity between cities. An international satellite gateway can be built using 1 medium construction team and 1 training team to establish international phone calling, international banking transactions, and international stock trading. The numbers of teams were estimated based on similar scale tasks for other resource packages in the scenario.

Table B-2. Resource packages for nationwide and international phone services

Resource Package	Description	Large Team	Medium Team	Training Team
$R_{11(10)}$	**Establish fiber optic network to provide nationwide calling in each city**	3		
$R_{11(11)}$	**Establish satellite gateway service for international calling in each city**		1	1

A total of 18 resource packages are available to establish regional police and fire emergency services. According to the CPA, over 10,000 radios were required to establish a national emergency service radio system (CPA, 2004:26). The quantity of radios required for each region's fire and police emergency system was calculated using each region's population. The total number of radios was multiplied by the percentage of the nation's total population that was living in each region. This quantity was then divided evenly among fire and police systems. There are three different resource packages for each region's fire or police emergency radio system that correspond to procuring 30%, 60%, or 100% of the required radio systems.

Table B-3. Resource packages for regional police and fire emergency services

Resource Package	Description	Radios
R_{121}	**Procure 30% of the required police comm. in Region 1**	312
R_{122}	**Procure 60% of the required police comm. in Region 1**	623
R_{123}	**Procure 100% of the required police comm. in Region 1**	1,039

A total of 9 resource packages are designed to improve the nation's postal system. According to a US Army Corps of Engineers web page, 30 post offices were renovated in Iraq (US Army Corps of Engineers, 2004). The total number of post offices was multiplied by the ratio of a city's population and the nation's total population.

Table B-4. Resource packages for citywide postal services

Resource Package	Description	Medium Team	Training Team
R_{131}	**Establish Citywide Postal Service in City 1**	2	2
R_{132}	**Establish Citywide Postal Service in City 2**	1	1
R_{133}	**Establish Citywide Postal Service in City 3**	3	3
R_{134}	**Establish Citywide Postal Service in City 4**	3	3
R_{135}	**Establish Citywide Postal Service in City 5**	13	13
R_{136}	**Establish Citywide Postal Service in City 6**	2	2
R_{137}	**Establish Citywide Postal Service in City 7**	1	1
R_{138}	**Establish Citywide Postal Service in City 8**	5	5
R_{139}	**Establish Citywide Postal Service in City 9**	1	1

Four other resource packages are available to establish nationwide and international postal service in each city. Large construction teams are used to build different numbers of regional distribution centers. The numbers of regional distribution centers in a given region are estimates. There is one regional distribution center for every

3 post offices in a region. An international postal service center can also be built using one large construction team and one training team.

Table B-5. Resource packages for nationwide and international postal services

Resource Package	Description	Large Team	Training Team
$R_{13(10)}$	Build Region 1 Postal Distribution Centers	2	
$R_{13(11)}$	Build Region 2 Postal Distribution Centers	6	
$R_{13(12)}$	Build Region 3 Postal Distribution Centers	3	
$R_{13(13)}$	Build International Service Center for international postal service	1	1

There are 30 financial market resource packages. There are 9 resource packages that are designed to establish citywide banking services and 1 resource package to establish nationwide banking services. According to the CPA, there are 16 private banks in Baghdad (Central Bank of Iraq, 2005). The numbers of banks for the remaining cities was calculated using the ratio of a city's population and City 5's population. One medium construction team and one training team was assigned to each bank.

Table B-6. Resource packages to establish citywide & nationwide banking services

Resource Package	Description	Medium Teams	Training Teams
R_{411}	Establish Banking Services in City 1	3	3
R_{412}	Establish Banking Services in City 2	1	1
R_{413}	Establish Banking Services in City 3	4	4
R_{414}	Establish Banking Services in City 4	3	3
R_{415}	Establish Banking Services in City 5	16	16
R_{416}	Establish Banking Services in City 6	2	2
R_{417}	Establish Banking Services in City 7	2	2
R_{418}	Establish Banking Services in City 8	6	6
R_{419}	Establish Banking Services in City 9	1	1

The other banking resource package requires 3 large construction teams to build a dedicated, nationwide fiber optic network for nationwide banking transactions (USAID, 2005).

Table B-7. Resource package for nationwide banking transactions

Resource Package	Description	Large Team
$R_{41(10)}$	**Build Dedicated Fiber Optic Network for Nationwide Banking Transactions**	3

There are 3 resource packages that are designed to establish a national stock exchange. The first resource package uses 1 large construction team to build the facilities and install equipment. The second resource package uses 1 training team to train all stock exchange personnel. The third resource package uses one policy team to draft stock exchange policies and standards. This policy team is considered a critical resource as it is the only resource that can achieve this subobjective.

Table B-8. Resource packages for the national stock exchange

Resource Package	Description	Large Team	Training Team	Policy Team
R_{421}	**Build a National Stock Exchange Facility**	1		
R_{422}	**Train Stock Exchange Personnel**		1	
R_{423}	**Develop Stock Exchange Policies and Standards**			1

The remaining resource packages are combinations of $5B, $7B, $10B, and $20B trade agreements to influence a given country to forgive a percentage of the total debt the nation owes to that country. The trade agreement values are notional estimates.

Table B-9. Resource packages for trade agreements to reduce national debt

Resource Package	Description
R_{431}	Trade Agreements lead to Country 1 forgiving $10B in debt
R_{432}	Trade Agreements lead to Country 1 forgiving $20B in debt
R_{433}	Trade Agreements lead to Country 1 forgiving $27B in debt
R_{434}	Trade Agreements lead to Country 2 forgiving $5B in debt
R_{435}	Trade Agreements lead to Country 2 forgiving $15B in debt
R_{436}	Trade Agreements lead to Country 2 forgiving $20B in debt
R_{437}	Trade Agreements lead to Country 3 forgiving $7B in debt
R_{438}	Trade Agreements lead to Country 3 forgiving $10B in debt
R_{439}	Trade Agreements lead to Country 3 forgiving $17B in debt
$R_{43(10)}$	Trade Agreements lead to Country 4 forgiving $5B in debt
$R_{43(11)}$	Trade Agreements lead to Country 4 forgiving $10B in debt
$R_{43(12)}$	Trade Agreements lead to Country 4 forgiving $20B in debt
$R_{43(13)}$	Trade Agreements lead to Country 5 forgiving $5B in debt
$R_{43(14)}$	Trade Agreements lead to Country 5 forgiving $7B in debt
$R_{43(15)}$	Trade Agreements lead to Country 5 forgiving $10B in debt
$R_{43(16)}$	Trade Agreements lead to Country 6 forgiving $5B in debt
$R_{43(17)}$	Trade Agreements lead to Country 6 forgiving $7B in debt

Cost estimates for each resource package were developed in the following manner. Lucent Technologies was awarded a contract for $25M to develop the restore traditional phone services in Baghdad (Haley, 2004). MCI WorldCom was awarded a $45M contract to install cellular communications systems in Baghdad (Telecommunications Industry Association, 2003). Therefore, a $65M cost estimate was used to establish citywide phone services in City 5. The remaining cost estimates for the other cities were based on the ratio of a city's population to City 5's population. Lucent was also awarded a $75M contract to rebuild Iraq's telecommunications infrastructure (Haley, 2004). This cost figure was used to estimate the cost of the nationwide fiber optic network. A notional cost estimate of $20M was used to represent the cost of the international satellite gateway.

Post office and commercial bank construction costs were developed using an online QuickCost Estimator provided by RSMeans (RSMeans, 2006). Using a 5,000 sq. ft. size estimate, commercial banks were estimated to cost $700K (RSMeans, 2006). City post offices were assumed to be about 5 times as large as a commercial bank, leading to a $1.9M construction cost (RSMeans, 2006). An additional $1.1M vehicle procurement cost was added to the construction cost, resulting in a total cost of $3M for each post office. Regional distribution centers and the international postal service center were estimated to cost $40M per facility (RSMeans, 2006).

The national stock exchange facilities were notionally derived as a fraction of the cost of the regional distribution centers. The policy and standards team was notionally assigned a cost of $4M. Each training team was assigned a cost of $500K.

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14. ABSTRACT
The purpose of this research was developing techniques to calculate the value of a resource within the context of campaign objectives, to identify competing objectives, and to identify conflicting objectives to improve a commander's ability to allocate limited resources. A methodology was developed to express a campaign's objective hierarchy in terms of a set of desired end states for the campaign's system of systems. Value theory was used to identify the resource's value in terms of the direct and indirect effects that are produced to achieve the campaign's objectives. Binding resource constraints within an integer program were used to identify the objectives that competed for the simultaneous use of limited resources. Conflicting objectives were identified using interaction tables. Collectively, the research translated doctrinal, effects-based operational concepts into actionable processes within deliberate planning and crisis action planning horizons.

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