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THESIS

AIR TASKING ORDER (ATO)
OPTIMIZATION MODEL

by

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This thesis addresses a known deficiency of theater level wargames. The problem is the ability to produce a timely, "flyable" Air Tasking Order (ATO) that effectively uses assigned aircraft. Wargame pace and the lack of an effective planning tool prevented strike planning from being effectively implemented in the ATO.

The model presented in this thesis offers a solution in the form of a computer based optimization model that produces ATO's. The model assigns strikes against all requested targets if there are sufficient assets, and it chooses which targets not to strike if assets are insufficient. The model decides which strike packages should be assigned against each target and which available launch sites should provide the assets required in the selected strike packages. The output is an ATO in which all assigned aircraft can reach their targets and are in fact available for tasking. This model solves in minutes on a personal computer and allows the pace of the wargame to be unconstrained by ATO production.

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AIR TASKING ORDER (ATO) OPTIMIZATION MODEL

by

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ABSTRACT

This thesis addresses a known deficiency of theater level wargames. The problem is the ability to produce a timely, "flyable" Air Tasking Order (ATO) that effectively uses assigned aircraft. During wargames conducted at the Naval War College, I observed that sound military analysis went into strike planning. However, the pace of the wargame and the lack of an effective planning tool prevented this strike planning from being effectively implemented in the ATO.

The model presented in this thesis offers a solution in the form of a computer based optimization model that produces ATO's. The model assigns strikes against all requested targets if there are sufficient assets, and it chooses which targets not to strike if assets are insufficient. The model decides which strike packages should be assigned against each target and which available launch sites should provide the assets required in the selected strike packages. The output is an ATO in which all assigned aircraft can reach their targets and are in fact available for tasking. This model solves in minutes on a personal computer and allows the pace of the wargame to be unconstrained by ATO production.

THESIS DISCLAIMER

The reader is cautioned that computer programs developed in this research may not have been exercised for all cases of interest. While effort has been made, within the time available, to ensure that the programs are free of computational and logic errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.

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EXECUTIVE SUMMARY

This thesis offers an ATO optimization program for use with the Enhanced Naval Wargame System (ENWGS) at the Naval War College. The program ensures that the best available aircraft are assigned to each target. Candidate target strike packages are designed during the pre-play phase of the game. The optimization model chooses the optimal strike packages based on availability of assets, distance to target, fuel availability, and JFACC preference. If there are insufficient assets available to strike all targets, the model ensures that the targets deemed most important are selected for strikes.

The optimization model benefits the JFACC cell by increasing the speed of ATO production and ensuring the output is a consistent, flyable tasking order. Given a target list, one person can produce an ATO for a given target list in a matter of minutes, vice hours using current manual methods. Currently, sound military analysis is used prior to game commencement. However, the game pace leads to aircraft assignments made in a hasty, manual fashion, with suboptimal results likely.

Presently, the pace of the wargame is constrained by ATO production. Using the ATO optimization model presented here

will allow the war game to progress at a much faster pace and will increase the training benefits of the wargame.

The model uses the following data. Each base or ship that can be used as a launch site has a list of aircraft available for tasking. Each target and required support mission is mapped to a "target type"' and each target type is given a set of potential strike packages comprised of appropriate sets of aircraft. The strike packages are ranked by preference.

The model's purpose is to answer three sets of detailed questions: (a) Which strike package should be assigned against each target? and (b) Which available site should provide the assets required in each selected strike package? (c) If there are insufficient assets, which targets should be left unstruck? Aircraft are assigned to targets based on availability, distance and preference. The model also ensures that all aircraft that require in-flight refueling have sufficient airborne gas available. If more fuel is needed, the model assigns more tanker aircraft to the tanker tracks, if available.

The model attempts to strike all targets and fly all support missions with the best available aircraft. Flying distances are minimized. There are several model constraints.

To make the ATO flyable, only aircraft deemed available by the subordinate commanders are used and aircraft are only tasked for missions and targets they can reach.

Another set of constraints enforced by the model is the single-sourcing requirement. This ensures that all aircraft of the same model that are assigned to the same target are launched from the same site. This constraint mirrors the real world considerations of crew briefing and flight leadership.

The model will assign aircraft for all requested targets and missions, if sufficient assets are available. If not, the model will recommend which targets or missions to omit based on availabilities and the user's priority.

Output of the optimization model is designed in the format of the ATO currently used in wargames at the Naval War College.

This model improves the training of all wargame participants. The ATO is produced with a flyable plan that improves the productivity of all warfare cells. This product requires fewer people to produce and can keep pace with any wargame pace, improving training for all hands.

The model and data management system are implemented with off-the-shelf software. The model is written in GAMS and the data may be stored in any database or spreadsheet.

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I would like to thank several people for their support and effort in this thesis project. Dr. Rosenthal has provided support, guidance, and patience throughout every stage. Without his help this would be a very different, less practical, less useful thesis.

The Naval War College Wargaming Department, especially CDR Bo Filanowicz, has been instrumental in this thesis. CDR Filanowicz provided the opportunity for me to visit the War College and define the problem. His knowledge of Operations Research and wargaming expertise ensured that the focus of my thesis is applicable to the War College.

I. INTRODUCTION

A. PROJECT BACKGROUND

This master's thesis is written in response to a wargaming requirement of the Naval War College. It addresses a known deficiency of theater level wargames. As in combat, wargames use an Air Tasking Order (ATO) to assign aircraft to missions. Wargames have personnel assigned from various commands with varied expertise. The ATO they produce is understandably slow in preparation and often unflyable due to poor tasking of assets. This thesis offers a solution in the form of a computer based optimization model for producing ATOs. The model's ATO makes better use of assets and takes much less time to produce.

During large Enhanced Naval War Game System (ENWGS) [Ref. 1] events, the ATO is used to assign the air assets of the various warfare commanders to target strikes and support missions. Presently, there is duplication of effort and a poor use of available resources during ATO production. Aircraft are sometimes poorly assigned. Many are over-tasked while others remain unused. Aircraft based in multiple locations are not always assigned from the best launch site. This is far from optimal. Often, the limiting factor in the speed of the game is promulgation of an ATO.

The effect of a slow, inefficient ATO is reduced training for all participants in the wargame. This thesis offers a solution that uses available assets better and produces the ATO more rapidly. The model improves the flow of the wargame. Training will be improved significantly for all participants.

In the capacity of a Naval Postgraduate School masters of science student, I observed ATO production during an ENWGS based wargame called SEACON 92, conducted at the Naval War College in November 1992. The Joint Force Air Component Commander (JFACC) cell, which is responsible for ATO production, had approximately 20 people assigned. There were nearly 300 total players in the two-week long wargame. The SEACON 92 game required an ATO for managing the air assets of several aircraft carriers, a Marine Amphibious Group, an Allied Air Group and numerous Air Force assets. These assets were distributed across many bases in several operating areas. Strikes were planned against multiple targets in diverse locations. The preferred pace of the wargame is an eight-to-one ratio of game time to real time. Unfortunately, slow ATO production prevented the game from accelerating to this pace. Moreover, the JFACC cell was frequently inefficient in the way it used the available aircraft assets of the different cells. Many assets went unused while others were tasked beyond their capabilities, ranges and availability. The huge amount of man hours with the accompanying poor ATO is the motivation for the production of this ATO model.

The ATO process is described in detail in the following sections. A basic explanation is that the ATO is an air plan of all the events required in strike planning. The assets used are those deemed available by the warfare commanders. The sites targeted are chosen by the Joint Targeting Board (JTB) in response to the Battle Force Commanders' intentions.

B. THE AIR TASKING ORDER

1. Purpose

JCS pub 3-56.23 describes the sequential procedures to be used for coordinating air efforts in a joint environment. After detailed planning is completed by the joint staff, the subordinate commanders advise the JFACC of the planned allocation of organic air assets required to conduct self defense missions, training and maintenance. In addition, any expected excess sorties are identified and transmitted to the JFACC via the excess sortie message. The JFACC then allots these excess sorties to the different subordinate commanders via a sortie allotment message and a common Air Tasking Order.

The JFACC receives a list of sorties available from the subordinate commanders. The JTB submits a list of targets to be attacked. The ATO produced by the JFACC must assign these targets to the available sorties. There ATO also contains support missions such as tanker missions, reconnaissance flights, Airborne Early Warning (AEW), and patrol flights, which assist the strike missions.

Each subordinate commander publishes an air plan. This plan includes the ATO scheduled flights and the flights the commander must fly to protect his base or ship and maintain readiness. These defensive events are not directly involved with attacking targets or strike support and are omitted from the data requirements of the ATO optimization model.

2. Terminology

The following terms and acronyms are specific to strike planning and ATO production.

- Airplan : the flight schedule
- Air Tasking Order (ATO): the document tasking all events involved in strike planning
- Battle Damage Assessment (BDA): estimate of damage to previously struck targets
- Combat Air Patrol (CAP) : missions flown by fighter aircraft to act as air interceptors
- Identification Friend or Foe (IFF) : the discrete radio codes used to identify friendly aircraft
- Joint Force Air Component Commander (JFACC) : the organization responsible for promulgation and execution of the ATO
- Joint Intelligence Center (JIC) : contained within the JFACC, it provides intelligence information to the JTB and JFACC
- Joint Targeting Board (JTB): the organization within the JFACC cell responsible for choosing the strike targets
- Sortie: A mission accomplished by a single aircraft
- Airborne Early Warning (AEW) : Aircraft used to detect hostile air

- Time On Top (TOT) : The time air assets are scheduled to be at a target

3. Actual ATO Implementation

During actual strike operations, such as Operation Desert Storm, the ATO is the master plan for all strike events. The JFACC organization is a large group commanded by an Air Force General whose deputy is a Navy Rear Admiral. Each subordinate commander has a representative who serves as liaison to the JFACC. The JTB within JFACC, presents a list of targets to be struck during a twenty-four hour period. This list is based on the Battle Force Commander's desires and information provided by the Joint Intelligence Command (JIC).

Initially the ATO is drafted two to three days prior to implementation. On the day prior to publication, a final draft is published which includes the Battle Damage Assessment (BDA) of previous attacks and the assets provided by the subordinate commanders via their respective excess sortie messages. A separate team within the JFACC monitors the progress of the ATO on the day it is executed. Any strikes that are unsuccessful for any reason are considered for the following day's ATO. The group monitoring ATO execution may redesignate targets for a strike or cancel events as the conflict warrants.

4. Actual Conflict ATO

During real world hostilities, the ATO is an extremely complex document. For each strike mission, the wartime ATO contains information on the target, the composition of aircraft, and the launch site for each type of aircraft, just as in a game. But the wartime ATO also designates the discrete codes the aircraft must set for identification (IFF), the Return-to-Force procedures that prevent friendly fire on aircraft egressing from target areas, and the controlling agency responsible for strike coordination, and the safety of flight information.

Wargame ATO's are not as detailed as in the real world. Weapons load out decisions are left to the different warfare cells. The wargame ATO designates targets and required support missions. The ATO assigns aircraft to the missions and a time line for the events. The personnel limitations of wargames, both in number and skill level, and the speed of wargames preclude much greater detail.

C. WARGAMES

1. Focus

Wargames try, as much as possible, to provide participants a sense of actual conflict. Games are an excellent forum for practicing tactics and strategies. The focus of wargames is to demonstrate and test the level of planning, coordination, and flexibility required during large scale conflicts. Some games are used to demonstrate the complexity of potential real world scenarios, while others enable commanders to evaluate the performance of their staffs.

Wargames are valuable in identifying problems and finding solutions.

The amount of time available and the military competence of the players dictate the level of detail of the game. The focus, regardless of the detail, is to provide participants a sense of the logistical enormity of planning and executing large conflicts.

2. Scope

Wargame size and scenario are normally constrained by the facilities and time allotted for the game. The model presented in this thesis is most applicable to large theater level games. These games normally have approximately twenty cells. Each cell represents a subordinate warfare commander and has between ten and twenty people assigned. The cell manning is based on the perceived tasking of that cell in the scenario. At the Naval War College a staff member is assigned to each group to serve as wargame facilitator and subject matter expert.

Participants do not deal with small scale warfare considerations. For example, games do not require players to actually control an airplane during its entire flight. The focus is the utilization of available assets given a particular scenario. Players must deal with the dynamics of losing assets and decide on a plan of attack that is flexible enough to deal with the activities of the enemy forces.

D. GOAL

1. JFACC Operations

The goal of this thesis is to improve the performance of players assigned to the JFACC cell and to enhance their training. The model performs many of the tasks of the real world JFACC organization. Currently, the enormity of the task is overwhelming. The speed and scale of the conflict does not lend itself to training. With proper planning and tools, the focus of the players is target designation and strike scheduling vice the drudgery of ATO manual promulgation.

The JFACC cell takes the desired targets from the JTB and creates a strike time line. The linear optimization model presented in this thesis produces an optimal mix of available assets to accomplish the task. Implementation of the ATO is also monitored from the JFACC, allowing successive ATOs to cover events that are missed. Often events lead to a change of targets or new missions. The JFACC cell needs to control these changes and adjust future plans accordingly.

In order for the linear optimization model to be effective, the JFACC cell members must plan during the pre-play phase. Each task, whether a target or support mission, should be put into a target-mission group. This will be based on target type (e.g., runway). Suitable strike packages are designed using the available types of aircraft. The JFACC cell is organized during this time. Some members are assigned to current day operations while others plan future ATOs.

2. ATO Model

The optimization model is used to produce the ATO. It chooses the best aircraft to perform the planned strikes. Distance to targets, availability of assets, and preferences are all incorporated in the model. Current databases which hold all the relevant information are used as inputs to the model. Inputs include JTB's target list, the excess sorties available and the predetermined strike packages. The goal is to provide the best strike packages for those targets deemed important by the JTB. This model, combined with effective prior planning, will lead to more efficient ATO planning.

The model is a mixed integer linear optimization model. It is written in GAMS[Ref. 2]. dBASE[Ref. 3] is used to store and format the data used by the GAMS model, though other database or spreadsheet software can be easily substituted as the interface to GAMS. The model achieves optimality by striking as many targets as possible as efficiently as possible. A series of constraints ensures that assets are used to the best of their ability. Chapter II deals with the formulation of the optimization model.

E. APPROACH

The optimization model is designed to be as generic as possible. Different wargames can have drastically different assets in use. The optimization model and data bases are independent. The model is designed to work with any feasible data set that contains the assets of that particular game. It works as long as the data has been entered for each asset. The model will look at the assets available and strike the targets with the best total use of assets. The packages assigned are based on the packages the players enter during the pre-play phase. The model balances the preference of the JFACC cell for each package with the distances the aircraft must travel to each target. The model ensures all aircraft of the same type assigned to the same mission are from the same launch site. This last constraint, called single sourcing, mirrors the real world considerations of crews briefing together and ensuring flight lead integrity.

Fuel is accounted for in this model as follows. It is assumed that all aircraft launch with a full bag. If the assigned task requires the aircraft to exceed the range that was entered as a parameter during pre-play, the model will ensure that enough tankers are available. Each aircraft has a maximum number of fuelings allowed. The distance penalty is more severe for each refueling, which discourages refueling if possible.

F. LIMITATIONS

There are some limitations in the optimization model. When the model checks the amount of in-flight fuel available it ignores the geographic position of the airborne tankers. This makes the gas availability constraint somewhat optimistic.

This model makes no attempt to forecast mission success. BDA still is performed outside the model. Factors such as aircraft attrition and weapon success are not figured automatically. The databases used must be updated to reflect this information.

II. FORMULATION

A. APPROACH

The purpose of the optimization model is to find the best match of available assets to designated targets and missions. Strike packages of different aircraft types that are capable of performing a support mission or successfully striking a target are identified in pre-play. These missions are flown by the best aircraft available within the constraints discussed in this chapter. If all targets can not be struck, the ATO model selects the targets in accordance with the target preferences of the user.

Optimization is ideal for this problem. It tries to get the best aircraft to the targets while ensuring all of the constraints are not exceeded. The objective function ensures the best deployment of aircraft for the ATO as a whole, not just for an individual mission or target.

B. INDICES

We use the following indices to formulate the optimization model:

a	assets
i	sites
j	targets
m	mission types
n	strike packages

A small example of the values over which these indices may range is:

$a \in \{A6,\ F18,\ B52,\ TLAM\}$
$i \in \{AIRBASE\text{-}A,\ CV72,\ DDG51\}$
$j \in \{PALACE\ BUNKER,\ ADEN\ AIRFIELD,\ SOUTH\ NAVY\ PIER\}$
$m \in \{AIRFIELD,\ TOMAHAWK,\ TANKER\}$
$n \in \{PACKAGE\ 1,\ PACKAGE\ 2,\ PACKAGE\ 3\}$

where j represents the actual target and m represents the target type or mission type. The n index represents the acceptable packages comprised of aircraft capable of flying the mission or conducting the strike. The model is versatile enough to accommodate much larger instances of the problem than the example given above.

C. DECISION VARIABLES

The primary decision variables of the optimization model are binary variables. Together they decide which strike package is used against each target and which site provides the assets required in the selected strike package. The first set of binary variables is:

X_{jn} = 1 if strike package n is assigned to target j.

0 if not

The second set of binary variables is:

Y_{aij} = 1 site i is authorized to provide assets a to target j.

0 if not

There are two other variables in the model. The first is a continuous integer variable:

Z_{aij} = The quantity of asset a assigned from launch site i to target j.

Variables Y and Z are closely related in that both are used to provide assets to targets from a launch site. They are not redundant, however. Both are needed because of the single-sourcing constraints.

There is also an elastic variable for target nonassisgment. It allows constraint violation at a cost that is entered as an input parameter. The elastic variables are:

E_j = 1 if target j is not assigned a strike in the ATO,

0 otherwise.

The cost of the elastic variables is prohibitively high, so that the non-strike option is invoked only when it is physically impossible to strike all targets with the available resources.

D. OBJECTIVE FUNCTION

The objective function is designed to maximize a weighted sum of the selected targets struck and the missions filled, less certain penalties. The model assigns the most efficient assets to th^ tasks by comparing the commanders' preferences with the capabilities of the aircraft:

$$MAXIMIZE \sum_{jn} EPREF_{jn} \cdot X_{jn} - \sum_{j} TPREF_j \cdot EPEN_j \cdot E_j - \sum_{aij} DPEN_{aij} \cdot Y_{aij}$$

where:

$EPREF_{jn}$ = The preference value of the strike package

$TPREF_j$ = The target preference
$EPEN_j$ = Elastic penalty for not striking a target
$DPEN_{aij}$ = Penalty value for distance an asset must fly to reach a target

The $EPREF_{jn}$ is a parameter chosen by the user prior to ATO production. It rates the relative desirability of the different candidate strike packages available for a mission or particular target type. The $DPEN_{aij}$ is a penalty that is computed using the range to the target and the combat radius of the particular aircraft. The $TPREF_j$ is a parameter that ensures the highest priority targets and missions are filled.

E. CONSTRAINTS

1. Target Strike Constraints

The first set of constraints ensures that each target is struck if possible, or a penalty is assigned. The strike constraints are:

$$\sum_{n} X_{jn} + E_j = 1, \quad \forall j$$

Since X_{jn} is a binary variable, this constraint ensures that either one package is assigned in its entirety or the penalty is assessed.

2. Demand Constraints

The second set of constraints ensures that the demand for assets at each target is met. The demand constraints are:

$$\sum_{i} Z_{aij} = \sum_{n} QTY_{ajn} \cdot X_{jn}, \quad \forall aj$$

where the input parameter QTY_{ajn} is defined as

QTY_{ajn} = The quantity of asset a in strike package n proposed for target j.

The left side of the equation represents the quantity of the asset allocated from a launch site to a target. The right side computes the demand for the asset as a function of the chosen strike package.

3. Single-Sourcing Constraints

The single-sourcing constraints ensure that all aircraft of the same kind that are assigned to the same target come from the same launch site. This prevents, for example, two carriers each providing two of the A6's required in an attack, which would violate flight leadership and common site briefing considerations. If different types of aircraft are required for a strike, they may come from different sources. An exception to the single-sourcing rule is made for tanker aircraft that perform in-flight refueling. The single sourcing constraints are:

$$\sum_{i} Y_{aij} \leq 1, \quad \forall a \neq tanker, \ \forall j$$

4. Supply Constraints

The optimization model ensures that aircraft are not tasked beyond their availability. These constraints are:

$$\sum_{j} Z_{aij} \leq AVAIL_{ia}, \quad \forall ia$$

where
$AVAIL_{ia}$ = Quantity of assets of type *a* available at launch site *i*.

The input parameter $AVAIL_{ia}$ is provided to the JFACC cell from the subordinate warfare commanders via the excess sortie message. The GAMS formulation of the model checks this constraint only when the site is the home base for assets that are potentially used on a target. The distance from the site to the target must be within the range of the assets.

5. Logical Constraints

The logical constraints, also known as variable upper bounds, are needed to ensure that the Z_{aij} variables governing asset allocation (via the demand constraint) are logically connected to the Y_{aij} variables which govern single-sourcing (via the single-sourcing constraints). These constraints are written

$$Z_{aij} \leq AVAIL_{ia} \cdot Y_{aij}, \quad \forall aij$$

and they guarantee that the Y's and Z's are nonzero for the same values of *a,i,j*. The logical constraints are generated and checked only for the *a,i,j* combinations corresponding to physically feasible taskings.

6. Fuel Constraints

Aircraft will often be tasked to fly missions that require in-flight refueling. In-flight refueling is common for military tactical aircraft. Our optimization model will ensure that enough gas is provided by the available tankers for all aircraft that need refueling to complete their missions. If enough gas cannot be provided, the model assigns aircraft within range or tasks additional tankers. Each aircraft has a parameter that defines the amount of fuel per tank the aircraft uses and a parameter detailing the number of times it can be fueled. The second parameter is only invoked during variable reduction and is discussed later. The Gas constraint is written:

$$\sum_{a \neq tanker,\, ij} Z_{aij} \cdot FILL_a \cdot floor(DIST_{ij} \div RANGE_a) \leq \sum_{a = tanker,\, ij} Z_{aij} \cdot GIVE$$

where:

$FILL_a$ = The amount of fuel the aircraft uses during midair refueling

$DIST_{ij}$ = The distance from the asset launch site to the target or mission area.

$RANGE_a$ = The designed combat radius of the aircraft.

$GIVE_a$ = The total fuel a tanker aircraft has to give.

floor = This function returns the greatest integer less than the operand.

The parameters FILL, RANGE, and GIVE are all entered by the game players prior to game commencement. The DIST value is computed using a modification of the GAMS library routine for great circle calculation (Appendix A).

This constraint sums all the aircraft that exceed their designed radius during a mission. The amount of fuel required is then summed and compared to the total amount airborne. If there is not enough fuel in the air and there are tankers available, more tankers are added to the flight schedule.

F. PENALTIES

1. Elastic Penalty

There are two penalties in this model. The first is the elastic penalty for not striking a target ($EPEN_j$). This penalty should be set high enough so that it is used only when asset limitations make it unavoidable. The objective function charges the EPEN for each target not attacked or mission not flown. It is multiplied by the relative importance of the corresponding targets. The model mixes assets as necessary to ensure the most complete coverage.

2. Distance Penalty

Each aircraft used in the model is given a combat radius that is entered as a parameter ($RANGE_a$). The distance penalty increases as the length of the mission approaches the range of the aircraft. Initially the penalty increases at a gradual rate (m1). When a combat radius is exceeded the aircraft must refuel from an airborne tanker. This in-flight refueling causes a jump in the distance penalty. After refueling there is a higher rate of penalty increase in order to account for crew fatigue and possible aircraft problems as distance increases. The distance penalty is computed by the following formula:

$$DPEN_{aij} = m1 \cdot (DIST_{ij} \div RANGE_a) \text{ if } DIST_{ij} \leq RANGE_a$$

$$DPEN_{aij} = 1 + m2 \cdot ((DIST_{ij} - RANGE_a) \div RANGE_a) \text{ if } RANGE_a \leq DIST_{ij}$$

where:
$m1$ = slope of DPEN when refueling not required
$DIST_{ij}$ = Distance from site i to target j
$RANGE_a$ = Range of asset a
$m2$ = slope of DPEN after refueling.

G. VARIABLE REDUCTION

The GAMS modeling language allows the model to be generated and solved efficiently. The GAMS dollar operator function ensures that variables and constraints are considered only for valid site-aircraft-target combinations. This allows the model to solve large problems much more quickly, than would be possible otherwise. For example, the variables Y_{aij} and Z_{aij} exist only for those a,i,j combinations that obey all of the following conditions:

- Asset a is available at site i.
- Target j can be reached by asset a from site i within the allowable number of refuelings.

- There exists at least one candidate strike package for target j that employs asset a.

The input parameter, $MAXFILLS_a$, is invoked only during variable reduction. $MAXFILLS_a$ represents the maximum number of fuelings an aircraft is allowed. It ensures that aircraft are only considered for targets that can be reached with in-flight refueling. The variable reduction reduces the number of variables and constraints considerably.

III. DATA REQUIREMENTS

The optimization model presented in this thesis is designed to work in any wargame. The model is generic, allowing it to be used with any sets of assets and targets. This chapter addresses the data that is required for targets and aircraft. JFACC cell members must make some generalizations and assumptions. The data is meant to be dynamic throughout the game in order to reflect changes in capabilities and requirements.

The information required is stored in four databases and is used to construct the GAMS data file. Much of the database information is constructed during pre-play. The four databases are: Target Information, Site Information, Asset Information, and Strike Package data. The following sections discuss the data required for the model.

A. TARGET DATA

The majority of the target information is determined during the pre-play phase of the wargame. During SEACON 92, a database of all potential orange (enemy) targets was presented to the JFACC cell prior to game commencement. This information must be organized to allow the ATO to rapidly respond to the targets chosen by the JTB.

1. Target Identifier

Each target will be given a name and a target identifier. The identifier will normally reflect the area where the target is located. Examples would be all targets in the ADEN theater are designated A-001 to A-050 sequentially from East to West. This identifier is used in the formulation of the optimization model as the index j. The identifiers can be different from one run of the model to the next. The structure of the identifier is left to the JFACC cell. Any form that organizes targets conveniently is acceptable.

The ATO also tasks many missions not associated with targets. These mission stations tasked by the ATO are planned, if possible, during pre-play. Combat Air Patrol (CAP) stations and Tanker tracks, for example, are chosen and given an identifier. All mission areas of the same type should be given similar names for ease of interpretation of the output.

2. Target Position

The position of each target is required for the great circle distance calculation. The calculations accept the latitude and longitude in degrees and minutes. Mission stations, such as CAP stations and tanker tracks, should use the center point of the area.

3. Target and Mission Type

The most important information required for each target and mission is the target type. The target type is used to categorize each target into a usable group. While each target is unique and may require a unique strike package, similar targets are grouped together as a target type. The first step is to create a list of target types. As each target from the database is examined during pre-play, it is grouped with other targets having similar attributes. Collectively these targets are a target type. If a target clearly does not fit any target type, it is acceptable to create a unique target type.

Examples of target types are Airfields, Hardened Bunkers, and Piers. All airfields in the target database may be given the target type airfield. There is great diversity among airfields in the data base, they may be better classified in several groups such as Large Airfield, Medium Airfield and Small Airfield, for example. The target type should try to capture as much information as possible.

The grouping of targets into target types should be based on the user's judgement concerning appropriate strike packages. Targets that seem different may be grouped together. For example, bridges and roads are different but are likely to have the same candidate strike packages. Therefore it is a good idea to group them into one target type, which might be called bridge/road.

If a target has special attributes such as CAP defense or SAM sites that are co-located, these defensive attributes are incorporated into the target type. For example, a target type may be expanded to AirfieldCAP.

Missions that are not targets, but require tasking by the ATO, are also given target types. Tanker tracks and CAP stations are examples. These can be subdivided if necessary. A CAP station that requires two aircraft as opposed to a station that requires four, are different target types.

4. Target Preference

The optimization model attempts to strike all targets and fill all missions. However, there may be situations when there are not enough assets in range to do all the JTB tasking. In this situation the target preference is used. The target preference separates each target into preference groups. A mission which must be flown if at all possible is given a high value. Missions not as critical are given lower values. Lower values are used for missions only to be flown if the assets are available.

These values are used in the objective function. The function is optimized if penalty values are minimized. Therefore the model fills all higher valued tasking before flying flights with lesser values.

If all flights are critical they can all be given high preference values. However, insufficient assets may preclude all targets being struck and the user would have no say in the process if all targets have the same priority. Distance and availability would then decide which targets to hit.

B. SITE DATA

The information required by the model for each site is relatively simple. Each site, *i* in the formulation, represents an airfield or ship where friendly aircraft are located.

1. Site Position

The latitude and longitude for each site is required to calculate the distance to each target. These distances are used to compute the distance penalty for each asset and thereby encourage efficient selection of launch sites.

2. Asset Availability

The game players representing the subordinate air commanders in the game have requirements outside the ATO, such as aircraft maintenance, check flights and self-defense. Each commander determines the excess sorties available for tasking and enters them in the model as $AVAIL_{ia}$.

C. ASSET INFORMATION

Prior to game commencement, an air order of battle is distributed. Information for each of the aircraft types is required for the optimization model. All of this information should be entered during the pre-play phase of the wargame. This information will probably not require modification during the play of the game. This data is entered in the ASSET database.

1. Range

Each aircraft available in the game must be assigned a range. The range represents the aircraft's combat radius. This distance is used as the $RANGE_a$ parameter. It is the unrefueled range of the aircraft. After each in-flight refueling the aircraft has its complete range available again. An aircraft that can perform different missions may have different combat radii. If an aircraft has distinct missions with different characteristics, it can be modeled as more than one aircraft type. An F-18 in fighter role may have a different range from an attack F-18, for example, so they should be entered separately in the model.

2. Allowable Refuelings

In each wargame many of the aircraft have the ability to refuel in-flight. Larger land based aircraft may not have this capability. Aircraft that can refuel are given a maximum number of refuelings. This mirrors the aircraft and crew limitations as flight time increases. Aircraft that cannot refuel in-flight are given the value one. A judgement is made as to how many tanks of gas each aircraft can receive in one flight. This value is $MAXFILLS_a$.

3. Fuel Availability

The amount of fuel that tanker aircraft have to distribute must be entered as the $GIVE_a$ parameter.

D. STRIKE PACKAGES

Earlier in this chapter target types were presented. Each target type is assigned candidate strike packages. Each of these strike packages is comprised of several aircraft, which, as a group can successfully attack the target or complete the mission. During the pre-play phase, the JFACC cell determines strike packages that are best suited for each target type. For support missions aircraft that can perform the mission are assigned. There may be only one combination of assets that can fill a mission. Special missions such as AWACS is an example of this.

Normally there are several strikes packages of aircraft that can successfully complete a mission. These candidate packages must be ranked for preference. For ease of use the JFACC cell should limit the number of candidate packages to a manageable size, probably three, four or five. They are ranked with the best package getting the highest value. If packages are equal they can be given the same value. Distance to target would then determines which package flies. A sample strike package follows:

```
Target Type:    Airfield
Package number: 1
Assets:         4 F/A-18
                1 EA-6
Preference:     3
```

The packages can be a mix of diverse aircraft. The model tries to optimize the ATO by assigning the highest preferred packages if those assets are available and within reasonable ranges. Sensitivity analysis on the effect of distance to preference on package selection is presented in Chapter IV.

E. DATABASE

dBASE IV was tested as the data formatting software. Any commercial database or spreadsheet software can format the data and interface with the optimization model.

IV. RESULTS

The goal of the optimization model contained in this thesis is to produce a better ATO in a shorter time period. This chapter addresses the model results and output in comparison with a manual ATO, using test data based on the SEACON92 wargame held at the Naval War College in November 1992.

A. MODEL OUTPUT

An example of the ATO model output is provided in Appendix D. The output gives the information from the ATO model necessary for ENWGS use. Results of sample ATOs produced by this model are discussed in the following sections. Results are considered in terms of time and optimality of the ATO produced.

1. Time

The principal benefit of this model is the speed with which the JFACC cell can produce ATOs. Much of the data is entered during the pre-play phase of the wargame. Data entry during the ATO production is minimal. The only information required at that time is the target, target type, target preference, target position, and sortie availability. The greatest personnel effort of ATO production is data entry. For a scenario with fifty targets and ten launch sites, data entry typically takes less than a half hour for one individual. Solve times are discussed in the next section.

a. *Solver Comparison*

Two solvers were used with the GAMS software during testing. The model requires an integer solution. Two available integer solvers that work with GAMS on PC's are ZOOM[Ref. 4] and XA[Ref. 5]. Both solve small ATO problems quickly. The XA solver proved superior. Solve times in XA are less than three minutes. There are some large scenarios that ZOOM is unable to solve. A comparison of the two integer solvers is listed in TABLE I.

TABLE I. SOLVE TIMES IN MINUTES AND SECONDS ON A 486/33

NUMBER OF TARGETS	XA	ZOOM
20	0:10	0:09
40	1:17	3:42
60	1:52	9:16
80	2:21	did not solve
100	2:42	did not solve

The output from the two solvers when they both obtain solutions are nearly identical. All comparative tests were run with relative optimality tolerance (OPTCR) of .25.

b. *Optimality Tolerance (OPTCR)*

GAMS allows the programmer to set a parameter that determines how close the solution is guaranteed to be to the optimal solution. An OPTCR value of .10 allows the program to stop when the objective function value is guaranteed within

10% of optimal. (The solver may actually achieve an optimal solution with OPTCR = .10, but there is no guarantee.) If the ATO model tries for the absolute optimal solution (OPTCR = 0.0), solve times exceed one hour, which may make the model impractical. Conversely, a higher setting (OPTCR = 0.35) solves quickly but the mix of aircraft assigned changes significant y. A fifty target data set was tested to find an ideal OPTCR setting for the ATO model. TABLE II shows the results.

TABLE II

OPTCR Setting	Solve Time	Sorties Changed
0.0	> 1 Hour	--
0.1	22 minutes	2
0.20	8 minutes	2
0.25	3 minutes	4
0.30	2 minutes	8

The ideally optimal solution (OPTCR = 0.0) is impractical due to the longer solve times. The .25 setting, with a solve time of 3 minutes and only four sorties out of fifty having different aircraft assigned, is the recommended setting.

2. Penalty Sensitivity Analysis

a. *Distance Penalty*

There are several pre-programmed parameters that can effect the outcome of the model. They effect the balance of the distance penalty to strike package preference. The objective function is designed so that a package that requires refueling loses, in effect, one preference rating. For example, a package with preference three that must refuel is equal to a package that has preference two but is within the combat radius of the aircraft.

There are two values that are used to compute the distance penalty as discussed in Chapter II. The first (m1) is the value that is used when the distance is less than the range of the aircraft. The second (m2) is used when the distance exceeds the range of the aircraft.

The m1 value is multiplied by the ratio of the distance to the range of the aircraft. The m2 value is higher to reflect the decreased effectiveness on combat aircraft as their flight time increases. If the m1 and m2 values are low the package with the higher preference is always chosen regardless of the distance the aircraft must travel. Conversely, high distance penalties lead to all strikes being flown by the closest available package vice more preferred packages. The ideal situation is a balance where a package that requires aircraft to exceed their range is equivalent to a strike package that is within the range of its aircraft but whose preference value is one less. During testing of the model the following values balanced distance and strike package preference:

$$m1 = .6$$
$$m2 = 1.0$$

These values were tested with aircraft tasked to targets at their maximum designed range. When used with the distance penalty equations, they traded distance for strike package preference effectively. *For example a S3 patrol plane* assigned to a patrol box was given preference value 3. When the tasked patrol station exceeded the combat radius of the S3 aircraft, a British Nimrod aircraft, which was closer, with preference value 3 was assigned.

b. Elastic Penalty

There is an elastic penalty $EPEN_j$, which is assigned to any target that is not struck or mission not flown. The model is designed to strike all targets if the assets are available. This penalty must take a value that is greater than the combined distance penalties assigned for aircraft striking a target, so that the model is never encouraged to leave a target unstruck. During testing the maximum combined distance penalties accrued by one target was 6. The EPEN is given a higher value to ensure that there is never a situation where not striking is better. This value is multiplied by the target preference ($TPREF_j$) to ensure higher priority targets are struck if assets are limited by availability or range.

V. CONCLUSIONS

A. MODEL USE

This model was presented to the Naval War College Wargaming Department on 27 August, 1993. As discussed earlier in this thesis, the model is integral to the JFACC process. It will be implemented upon purchase of the GAMS software.

The Naval War College intends to tie the ATO optimization model into commercial database software. There are several off-the-shelf database products being considered. Integration of the GAMS data files with a data base is an easy process.

The War College Wargaming Department has discussed further potential uses of the ATO model. Force-planning modelling can be done by analyzing the Navy's ability to participate in scenarios where carrier based aircraft must fly long distances. The model is designed for use with wargames, but the optimization principles also apply to real world ATO production. This model would be an asset in the JFACC process.

The War College is attempting to conduct joint wargames with Army and Air Force wargaming centers. This model produces an ATO that incorporates the assets of the different services, therefore assisting the Navy in participating in joint exercises.

B. REFINEMENTS

There are further refinements that can be made in the future if the War College deems necessary. Presently, time is considered in block segments. The model can be altered to look at time continuously. Data for asset availability is not currently collected this way. If, in the future, this is required the GAMS formulation can be adjusted.

The model output is presented in Appendix D. This ATO format is designed for ease of use with ENWGS wargames. The outputted ATO can be adjusted for different scenarios.

C. FURTHER RESEARCH PROJECTS

The optimization model is the "engine" that produces the optimal ATO. There are several potential projects that can be pursued to further this model. The first is a Battle Damage Assessment model. Using an object oriented simulation language a prediction of strike packages against targets could be produced. This information could then be used to update the target data base. This model would greatly assist the JFACC cell in future planning and further speed wargame planning.

Another potential project is a weapons versus target approach. This is beyond the scope of wargames but within the realm of optimization. It would use the information contained in the MISM's to optimize the weapons load out for each package. Weapons availability at each site would the become part of the data structure. This level of detail approaches that required in actual conflict.

D. RECOMMENDATIONS AND CONCLUSIONS

This model is designed to enhance the ATO production of the JFACC cell during wargames. Upon implemenatation this model will save manhours in ATO production and increase training for all wargame participants. If the data is maintained in a useable form, the ATO process will be efficient and easy to execute. Wargame pace should no longer be constrained by the JFACC cell.

APPENDIX A. GAMS FORMULATION

```
$TITLE    Naval  Postgraduate  School  AIR  TASKING  ORDER
OPTIMIZATION MODEL (ver. 93/08/01)
$offupper offsymxref offsymlist offuellist inlinecom { }
$ontext

      By:          LT. Matthew H. Dolan, USN
                   Operations Research Department
                   Naval Post Graduate School
                   Monterey, California 93943

      ADVISOR:     DR. Richard E. Rosenthal
                   Operations Research Department
                   Naval Post Graduate School
                   Monterey, California 93943

      Date:        13 April 93

      Description: This model is offered as part of a masters
                 degree thesis.  It is intended for use at the
                 Naval War College. This model creates an Air
                 Tasking Order(ATO) for use with ENWGS wargames.
                 Linear Integer optimization is used to create
                 an ATO by matching available assets with
                 targets or missions.  Strike packages are
                 created by game players prior to game
                 commencement.  The model Databases are stored
                 in DBASE IV files.
$offtext
options
   limrow    =     0
   limcol    =     0
   solprint  =    off
   mip       =     xa
   rmip      =     xa
   optcr     =   0.25  {optimality tolerance: values closer to
                        zero may give better solutions but
                        will take longer}
   iterlim   = 5000000
   reslim    =  150000   {maximum solve time in seconds}
   integer2  =     122
   ;

SETS
   A   assets
   I   sites
```

```
   J   targets
   N   strike packages
   M   mission types
   TYPE  target type
   K    coordinates
   ;

$INCLUDE ATO.DAT

PARAMETERS
QTY(a,j,n)    quantity of asset a in strike package n on
              target j
EPREF(j,n)    effectiveness-based preference of strike package
USED(a,j)     checks if asset is potentially  used against
              target
EPEN(j)       Elastic penalty for not striking target j
DPEN(a,i,j)   Penalty for travel distance
JMAP(j,m)     Mapping parameter
TPREF(j)      Target Preference of target j
XSCALE        Objective function scale factor for strike
              preferences
ESCALE        Objective function scale factor for elastic
              penalties
DSCALE        Objective function scale factor for strike
              distance
$INCLUDE ATO.DIS

QTY(a,j,n)  =  SUM(m $ TYPE(j,m),STRIKEDATA(m,n,a,"QUANTITY"))
;
EPREF(j,n) = SUM(m $ TYPE(j,m), SMAX( a,
               STRIKEDATA(m,n,a,"PREFERENCE")));
USED(a,j) = SUM(m $ TYPE(j,m), SUM( n ,
               STRIKEDATA(m,n,a,"QUANTITY")) );

* Objective function tuning parameters.
EPEN(j)     =  100 ;
DPEN(a,i,j)$(AVAIL(i,a)   and   USED(a,j)   and(DIST(i,j)   LE
                    RANGE(a)))
            =  m1*((DIST(i,j)/RANGE(a)) );
DPEN(a,i,j)$(AVAIL(i,a)   and   USED(a,j)   and(DIST(i,j)   GE
                    RANGE(a)))
            = 1 + m2*((DIST(i,j)-RANGE(a))/ RANGE(a) );
XSCALE      =  1 ;
ESCALE      =  1 ;
DSCALE      =  1 ;


BINARY VARIABLES
   X(j,n)      Strike package assigned to target
   Y(a,i,j)    Site authorized to provide asset to target
   ;
```

```
POSITIVE VARIABLES
   E(j)         Elastic variable for not striking target
   Z(a,i,j)    Quantity of asset allocated from site to target
   ;

FREE VARIABLE
   OBJ          Objective variable
   ;

EQUATIONS
   STRIKE(j)      Strike each target with exactly one package
   DEMAND(a,j)    Meet demand for assets at each target
   SINGLE(a,j)    Use single site as source of each asset for
                  each  target
   SUPPLY(a,i)    Observe asset availability at sites
   LOGICAL(a,i,j)  Variable upper bound relating Y and Z
   GAS            Ensures enough gas is available
   OBJDEF
   ;



STRIKE(j)..
      SUM( n $ EPREF(j,n),  X(j,n) )  +  E(j)   =E=  1 ;

DEMAND(a,j) $ USED(a,j) ..
      SUM( i $ (AVAIL(i,a) and (Dist(i,j) LE
               MAXFILLS(a)*RANGE(a))),  Z(a,i,j))
      =E=
      SUM( n ,QTY(a,j,n) * X(j,n) ) ;

{A single launch site is used for all aircraft types.  The
only exception is tankers.  Tankers may come from any launch
source}

SINGLE(a,j) $( USED(a,j)and (GIVE(a) eq 0)) ..
      SUM( i $ (AVAIL(i,a) and (Dist(i,j) LE
                    MAXFILLS(a)*RANGE(a))), Y(a,i,j) )
           =L=   1 ;

SUPPLY(a,i) $ AVAIL(i,a) ..
      SUM(    j    $    (USED(a,j)    and    (Dist(i,j)    LE
                    MAXFILLS(a)*RANGE(a))), Z(a,i,j) )
           =L=
           AVAIL(i,a)  ;
LOGICAL(a,i,j) $ (AVAIL(i,a) AND USED(a,j)  and
                     (Dist(i,j) LE MAXFILLS(a)*RANGE(a)) ) ..
           Z(a,i,j)
           =L=
           AVAIL(i,a) * Y(a,i,j) ;
 GAS ..
```

```
     SUM( (a,i,j) $(    (DIST(i,j) GE RANGE(a))
                    and (DIST(i,j) LE MAXFILLS(a)*RANGE(a))
                    and AVAIL(i,a)
                    and USED(a,j) ),
          Z(a,i,j)*(FILL(a)* FLOOR(DIST(i,j)/RANGE(a))) )
          =L=
     SUM((a,i,j) $( GIVE(a) and used(a,j) and AVAIL(i,a)),
          Z(a,i,j)*GIVE(a)) ;

 OBJDEF..
      XSCALE *  SUM( (j,n),  EPREF(j,n) * X(j,n) )
    - ESCALE *  SUM( j, TPREF(j)*EPEN(j) * E(j) )
    - DSCALE *  SUM( (a,i,j) $ (AVAIL (i,a) AND USED(a,j)
      and (Dist(i,j) LE MAXFILLS(a)*RANGE(a)) ),
      DPEN(a,i,j) * Y(a,i,j) )
    =E=
    OBJ ;

MODEL  ATO  /ALL/ ;

SOLVE  ATO  USING  MIP  MAXIMIZING  OBJ ;


FILE RES /ATO.OUT/;
PUT RES;
     put system.title /
     put "Date/time generated:      " system.date,"      "
system.time //

     put ">>>>>>>>>>>    AIR TASKING ORDER    <<<<<<<<<<<" /
     put ""/
     put "TARGET     LAUNCH     AIRCRAFT      TIME ON TOP"/
     put "           SITE                                "/
     put "_______________________________________________"/
     put ""/

LOOP((j,a,i) $ Z(a,i,j),
     put   j.TL:11,   i.TL:11,   z.L(a,i,j):3:0,   a.TL:11,
TIME(j):6:0/;

     put ""/;
           );

if ( sum(j,e(j)) gt 0.01,
     put "    THE FOLLOWING TARGETS WERE NOT ASSIGNED"/
     put " "/
LOOP(j $ E(j),
     put j.TL:11/;
     put ""/;
         );
else
```

```
     put "    ALL TARGETS WERE ASSIGNED" / ) ;
DISPLAY DIST
DISPLAY DPEN
DISPLAY  X.L, Z.L ;
parameter  atorep(j,a,i,*)  ATO Summary Report ;
atorep(j,a,i,"Sorties")  =  z.L(a,i,j) ;
atorep(j,a,i,"Distance")  =  dist(i,j) $ z.L(a,i,j) ;
atorep(j,a,i,"Timeontop") =  time(j) $ z.L(a,i,j) ;
OPTION ATOREP:0:3:1 ;
display atorep ;
```

APPENDIX B. SAMPLE DATA SET

```
sets
   A     assets
   /
           A6, F18, F14,S3B,EA6,E2C,Thawkc,P3C { Navy }
           B52,E3A,KC10,J8,BNMROD                {SAC}
           F117, F111, EF111, F15      {TAC}
           KC130, AV8B,EA6M,F18M         {USMC}
   /
   I      sites
   /        AirBase-01 * AirBase-05, MAG1, MAG2, Carrier-A,
          Carrier-B, Cruiser-A, Cruiser-B/
   J      targets
   /        Targ-001 * Targ-020, AWACS1, TEXACOA, TEXACOB,
          TEXACOC, CAPA, CAPB, CAPC, CAPD, CAPS, JTRACK,
          GRND1,GRND2,PAT1,PAT2/
   M      mission type (target type)
   /        AIRFLDLG       Large Airfield
            AIRFLDSM       Small Airfield
            AIRFLDN        Airfield at Night
            BRGROD         Bridge or Road
            BRGRODN        Bridge or Road at Night
            BLDG           Building
            BLDGN          Building at Night
            HBUNK          Hardened Bunker
            TLAM           Tomahawk Target
            TNKRA          Airforce Tanker
            TNKRM          Marine Corps Tanker Station
            CAP2           2 Plane CAP Station
            CAP4           4 Plane CAP Station
            AEW            AWACS Station
            RECCE          Recconasance
            PATROL         Maritime Patrol
            SUCAP          Surface CAP
            JSTARS         J-8 Patrol
            AGRND          Air-to-Ground Support
            /
   TYPE(J,M)
   /      Targ-001.AIRFLDLG
          Targ-002.BLDGN
          Targ-003.BRGROD
          Targ-004.AIRFLDN
          Targ-005.TLAM
          Targ-006.AIRFLDSM
          Targ-007.BLDG
          Targ-008.BRGROD
```

```
          Targ-009.BRGRODN
          Targ-010.RECCE
          Targ-011.RECCE
          Targ-012.TLAM
          Targ-013.BRGRODN
          Targ-014.AIRFLDN
          Targ-015.AIRFLDSM
          Targ-016.TLAM
          Targ-017.HBUNK
          Targ-018.BRGROD
          Targ-019.HBUNK
          Targ-020.AIRFLDLG
          AWACS1.AEW
          TEXACOA.TNKRA
          TEXACOB.TNKRM
          TEXACOC.TNKRM
          JTRACK.JSTARS
          CAPA.CAP2
          CAPB.CAP2
          CAPC.CAP4
          CAPD.CAP4
          CAPS.SUCAP
          GRND1.AGRND
          GRND2.AGRND
          PAT1.PATROL
          PAT2.PATROL
          /
   N      strike packages
   /         Package-1 * Package-3 /
   ;

TABLE  STRIKEDATA(m,n,a,*)

                                      QUANTITY   PREFERENCE

AIRFLDLG . Package-1 . A6                6            3
AIRFLDLG . Package-1 . F14               2
AIRFLDLG . Package-1 . EA6               1
AIRFLDLG . Package-2 . B52               1            5
AIRFLDLG . Package-3 . F117              2            1
AIRFLDLG . Package-3 . EF111             1
AIRFLDSM . Package-1 . A6                6            5
AIRFLDSM . Package-1 . F14               2
AIRFLDSM . Package-1 . EA6               1
AIRFLDSM . Package-2 . F111              2            5
AIRFLDSM . Package-2 . EF111             1
AIRFLDSM . Package-3 . F117              2            1
AIRFLDN .  Package-1 . F117              2            5
AIRFLDN .  Package-2 . A6                4            3
AIRFLDN .  Package-2 . F14               6
```

```
RECCE    . Package-1 . F14        2     5
RECCE    . Package-2 . F15        2     5
BLDG     . Package-1 . F111       2     5
BLDG     . Package-1 . EF111      1
BLDG     . Package-2 . AV8B       4     4
BLDG     . Package-2 . EA6        1
BLDGN    . PACKAGE-1 . F117       2     5
JSTARS   . PACKAGE-1 . J8         1     5
BRGROD   . Package-1 . F18        6     5
BRGROD   . Package-1 . F14        2
BRGROD   . Package-1 . EA6        1
BRGROD   . Package-2 . F111       2     3
BRGROD   . Package-3 . F117       4     2
BRGRODN  . Package-1 . F117       2     5
BRGRODN  . Package-2 . F111       2     3
BRGRODN  . PACKAGE-2 . EF111      1
BRGRODN  . PACKAGE-3 . A6         4     3
BRGRODN  . PACKAGE-3 . EA6        1
HBUNK    . Package-1 . A6         4     4
HBUNK    . Package-1 . EA6        1
HBUNK    . Package-1 . F14        2
HBUNK    . Package-2 . F117       2     4
HBUNK    . Package-3 . THAWKC     6     2
TLAM     . Package-1 . THAWKC     2     3
TLAM     . Package-2 . THAWKC     6     5
SUCAP    . package-1 . A6         2     5
SUCAP    . Package-2 . S3B        2     4
SUCAP    . Package-3 . F15        6     3
AEW      . Package-1 . E3A        1     5
AEW      . Package-2 . E2C        1     2
AEW      . Package-3 . E3A        2     1
TNKRA    . Package-1 . KC10       2     5
TNKRA    . Package-2 . KC10       3     4
TNKRA    . Package-3 . KC10       4     3
TNKRM    . Package-1 . KC130      1     5
TNKRM    . Package-2 . KC130      2     4
TNKRM    . Package-3 . KC130      3     3
CAP2     . Package-1 . F15        2     5
CAP2     . Package-2 . F14        2     4
CAP2     . Package-3 . F18        2     3
CAP4     . Package-1 . F14        4     5
CAP4     . Package-2 . F15        4     5
AGRND    . Package-1 . AV8B       4     5
AGRND    . Package-1 . EA6M       1
AGRND    . Package-2 . F18M       4     3
AGRND    . Package-2 . EA6M       1
PATROL   . Package-1 . P3C        1     3
PATROL   . Package-2 . BNMROD     1     2

;
```

```
PARAMETER TIME(J)      Time on TOP
/
TARG-001          270800
TARG-002          270800
TARG-003          270830
TARG-004          270850
TARG-005          270900
TARG-006          270900
TARG-007          270930
TARG-008          270930
TARG-009          271000
TARG-010          271030
TARG-011          271100
TARG-012          271130
TARG-013          271230
TARG-014          271300
TARG-015          271300
TARG-016          271500
TARG-017          271530
TARG-018          271600
TARG-019          271600
TARG-020          271600
AWACS1            270800
TEXACOA           270800
TEXACOB           270830
TEXACOC           270830
CAPA              270800
CAPB              270900
CAPC              270930
CAPD              271000
CAPS              270900
JTRACK            270800
GRND1             270830
GRND2             270900
PAT1              270800
PAT2              270800
/
;

TABLE LOC(i,*)
                  LAT-DEG   LAT-MIN   LONG-DEG   LONG-MIN
AIRBASE-01          20        05         58         15
AIRBASE-02          24        02         57         50
AIRBASE-03          25        00         46         15
AIRBASE-04          23        00         46         00
AIRBASE-05          20        00         45         00
MAG1                26        30         55         00
MAG2                27        30         55         00
CARRIER-A           20        00         65         00
Carrier-B           24        00         55         00
```

```
Cruiser-A          20        30        60        00
Cruiser-B          20        30        60        15

TABLE COORD(j,*)
                LAT-DEG   LAT-MIN   LONG-DEG  LONG-MIN
TARG-001           27        15        56        30
TARG-002           32        00        57        25
TARG-003           36        15        52        20
TARG-004           32        15        56        00
TARG-005           32        00        57        00
TARG-006           33        15        58        00
TARG-007           32        30        56        15
TARG-008           34        15        55        15
TARG-009           33        15        58        00
TARG-010           32        30        56        15
TARG-011           34        15        55        15
TARG-012           32        15        58        00
TARG-013           33        15        55        00
TARG-014           34        10        57        00
TARG-015           35        10        56        00
TARG-016           32        15        54        00
TARG-017           33        30        53        00
TARG-018           33        22        55        30
TARG-019           32        29        54        28
TARG-020           34        16        52        25
AWACS1             24        00        55        15
TEXACOA            23        30        55        00
TEXACOB            23        00        52        00
TEXACOC            22        33        55        00
CAPA               24        30        55        00
CAPB               24        00        53        00
CAPC               25        00        54        00
CAPD               26        00        55        00
CAPS               28        00        53        00
JTRACK             23        00        54        00
GRND1              28        00        56        00
GRND2              27        00        57        00
PAT1               26        00        54        30
PAT2               23        00        53        00
;

SCALARS
m1    short range slope            /.6/
m2    long range slope             /1.0/
;

PARAMETER   TPREF(j)     Target Preference Group
/
TARG-001          2
TARG-002          3
```

```
TARG-003          3
TARG-004          1
TARG-005          1
TARG-006          2
TARG-007          2
TARG-008          3
TARG-009          2
TARG-010          3
TARG-011          2
TARG-012          1
TARG-013          1
TARG-014          3
TARG-015          3
TARG-016          3
TARG-017          2
TARG-018          3
TARG-019          2
TARG-020          2
AWACS1            3
TEXACOA           3
TEXACOB           3
TEXACOC           2
CAPA              3
CAPB              2
CAPC              2
CAPD              2
CAPS              3
JTRACK            3
GRND1             3
GRND2             2
PAT1              3
PAT2              2
/
;



PARAMETER  AVAIL(i,a)  Asset availability at launch sites
/
AirBase-01 . F111       18
AirBase-01 . EF111       8
AirBase-01 . KC10        4
AirBase-02 . B52         8
AirBase-02 . E3A         3
AirBase-03 . F117       24
AirBase-03 . F15        24
AirBASE-04 . KC10        6
AirBase-05 . E3A         4
AirBase-05 . J8          3
AirBase-05 . P3C         4
```

```
AirBase-05  . BNMROD      3
Carrier-A   . A6         12
Carrier-A   . EA6         6
Carrier-A   . F14        12
Carrier-A   . F18        12
Carrier-A   . E2C         2
Carrier-A   . S3B         4
Carrier-B   . A6         16
Carrier-B   . EA6         3
Carrier-B   . F14        12
Carrier-B   . F18        12
Carrier-B   . E2C         2
Carrier-B   . S3B         2
Cruiser-A   . THAWKC     20
Cruiser-B   . THAWKC      8
MAG1        . AV8B       12
MAG1        . KC130       2
MAG1        . EA6M        4
MAG2        . F18M       24
MAG2        . EA6M        4

/
;

PARAMETER RANGE(a)
/
A6                      900
F18                     600
F18M                    600
S3B                     800
AV8B                    500
KC130                  1500
F14                     800
EA6                     900
EA6M                    900
B52                    2000
F117                    600
F111                   1000
EF111                  1000
F15                     900
E3A                     900
E2C                     500
KC10                   1000
THAWKC                  900
J8                     1000
P3C                    1200
BNMROD                 1200
/
;
```

```
PARAMETER FILL(a)   How much gas used during midair
refueling
/
A6                        4
F18                       3
F18M                      3
S3B                       6
F14                       4
EA6                       3
EA6M                      3
F117                      3
AV8B                      2
F111                      8
EF111                     8
F15                       4
E3A                      10
/
;
PARAMETER GIVE(a)     Gas to give
/
KC10                    100
KC130                   100
/
;
PARAMETER MAXFILLS(a)  Maximum aircraft refuelings allowed
/
A6                        3
F18                       3
S3B                       2
F18M                      3
F14                       3
EA6                       3
EA6M                      2
KC130                     1
AV8B                      3
B52                       1
F117                      2
F111                      2
EF111                     2
F15                       3
E3A                       1
E2C                       1
KC10                      1
THAWKC                    1
J8                        1
P3C                       1
BNMROD                    1
/
;
```

APPENDIX C. GREAT CIRCLE DISTANCE CALCULATION

```
SETS
K           coordinates
/           X-AXIS, Y-AXIS, Z-AXIS/
;
SCALARS
PI     trigonometric constant       /3.141592653/
R      radius of earth              /3959/
;
PARAMETERS
   LAT(I)       Latitude of Launch Site
   LONG(I)      Longitude of Launch Site
   LATT(J)      Latitude of Target
   LONGT(J)     Longitude of Target
   UK(I,K)      Site Point in Cartesian Coordinate
   UKT(J,K)     Target Point in Cartesian Coordinate
   USEG(I,J)    Straight line distance between points
   UDIS(I,J)    Great Circle Distance in Unit Spheres
   DIST(I,J)    Great Circle distance in Miles;

 LAT(i) = (LOC(i,"LAT-DEG") + LOC(i,"LAT-MIN") / 60)*PI/180;
 LONG(i)= (LOC(i,"LONG-DEG") + LOC(i,"LONG-MIN") /
60)*PI/180;
 LATT(j) = (COORD(j,"LAT-DEG") + COORD(j,"LAT-MIN") /
60)*PI/180;
 LONGT(j)= (COORD(j,"LONG-DEG") + COORD(j,"LONG-MIN") /
60)*PI/180;

 UK(i,"X-AXIS") = COS(LONG(i))*COS(LAT(i));
 UK(i,"Y-AXIS") = SIN(LONG(i))*COS(LAT(i));
 UK(i,"Z-AXIS") =              SIN(LAT(i));

 UKT(j,"X-AXIS") = COS(LONGT(j))*COS(LATT(j));
 UKT(j,"Y-AXIS") = SIN(LONGT(j))*COS(LATT(j));
 UKT(j,"Z-AXIS") =               SIN(LATT(j));

 USEG(i,j) = SQRT(SUM(K, SQR(UK(i,K)-UKT(j,K))));
 UDIS(i,j) = PI;
 UDIS(i,j)$(USEG(i,j) LT 1.99999) = 2 * ARCTAN(USEG(i,j)/2

/SQRT(1-SQR(USEG(i,j)/2)));

 DIST(i,j) = R*UDIS(i,j);
```

APPENDIX D. SAMPLE OUTPUT

Naval Postgraduate School AIR TASKING ORDER OPTIMIZATION MODEL (ver. 93/08/01)
Date/time generated: 93/08/27 11:01:53
>>>>>>>>>>> AIR TASKING ORDER <<<<<<<<<<<<

TARGET	LAUNCH SITE	AIRCRAFT	TIME ON TOP
TARG-001	AIRBASE-02	1B52	270800
TARG-002	AIRBASE-03	2F117	270800
TARG-003	AIRBASE-01	2F111	270830
TARG-004	AIRBASE-03	2F117	270850
TARG-005	CRUISER-A	6THAWKC	270900
TARG-006	AIRBASE-03	2F117	270900
TARG-007	AIRBASE-01	2F111	270930
TARG-007	AIRBASE-01	1EF111	270930
TARG-008	AIRBASE-01	2F111	270930
TARG-009	AIRBASE-03	2F117	271000
TARG-010	CARRIER-B	2F14	271030
TARG-011	CARRIER-B	2F14	271100
TARG-012	CRUISER-A	6THAWKC	271130
TARG-013	AIRBASE-03	2F117	271230
TARG-014	AIRBASE-03	2F117	271300
TARG-015	AIRBASE-03	2F117	271300
TARG-016	CRUISER-A	6THAWKC	271500
TARG-017	CARRIER-B	4A6	271530
TARG-017	CARRIER-A	2F14	271530
TARG-017	CARRIER-A	1EA6	271530
TARG-018	AIRBASE-01	2F111	271600
TARG-019	AIRBASE-03	2F117	271600
TARG-020	AIRBASE-03	2F117	271600
TARG-020	AIRBASE-01	1EF111	271600
AWACS1	AIRBASE-05	1E3A	270800
TEXACOA	AIRBASE-01	2KC10	270800
TEXACOB	MAG1	1KC130	270830
TEXACOC	MAG1	1KC130	270830
CAPA	AIRBASE-03	2F15	270800
CAPB	AIRBASE-03	2F15	270900
CAPC	CARRIER-B	4F14	270930
CAPD	CARRIER-B	4F14	271000
CAPS	CARRIER-B	2A6	270900
JTRACK	AIRBASE-05	1J8	270800
GRND1	MAG1	4AV8B	270830
GRND1	MAG1	1EA6M	270830
GRND2	MAG1	4AV8B	270900
GRND2	MAG2	1EA6M	270900
PAT1	AIRBASE-05	1P3C	270800

PAT2 AIRBASE-05 1P3C 270800
ALL TARGETS WERE ASSIGNED

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