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Models for optimizing the mix of air launched missiles for repair processing

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THESIS

MODELS FOR OPTIMIZING THE MIX OF
AIR LAUNCHED MISSILES FOR
REPAIR PROCESSING

by

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and
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Models for Optimizing the Mix of Air-Launched Missiles for Repair Processing

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ABSTRACT

This thesis proposes three linear programming models for the Naval Air Systems Command to use in planning the repair of air-launched missiles through the Naval Weapons Stations. Specific emphasis is placed on the development of three models to aid the workload planner in determining the optimal mix of air-launched missiles to induct for repair each quarter at intermediate level maintenance facilities.

TABLE OF CONTENTS

I. INTRODUCTION

A. BACKGROUND

The research for this thesis is concerned with the logistics of air-to-air and air-to-ground missiles. Specific emphasis is placed on the development of models to determine the optimal mix of air launched missiles (ALMs) to induct for repair each quarter at intermediate level maintenance facilities. The Navy operates three such repair facilities.

A set of three models are described which are intended to assist in managing the missile repair process. These models allow for effective control of missile readiness objectives, maintenance budgets, and repair priorities.

There are seven different types of air launched missiles that make up the missile inventory system. These are further broken out into twenty different models. There are three air-to-air missiles, (SIDEWINDER, SPARROW and PHOENIX) and four air-to-ground missiles, (WALLEYE, SHRIKE, HARM, and HARPOON).

The following is a basic description of the missiles and the number of different models currently in the inventory.

SIDEWINDER - Four different models are currently in the inventory. SIDEWINDER is an air-to-air missile with an infrared guidance system.

SPARROW - Six models are included in the inventory. SPARROW is used in two applications: air launched and ship launched. Both types of launches use semi-active homing guidance systems.

PHOENIX - There is one model in the inventory. PHOENIX is an air-to-air missile an with active homing guidance.

WALLEYE - Four models are in the inventory. WALLEYE is an air-to-ground missile with television self guidance.

SHRIKE - One model is in the inventory. SHRIKE is an air-to-ground missile with a passive, anti-radiation guidance system.

HARM - One model is in the inventory. It is an air-to-ground missile designed to detect anti-aircraft systems with a passive anti-radiation guidance system.

HARPOON - Three models are in the inventory. They are capable of being launched from aircraft, surface ships, or submarines. HARPOON is an active radar guidance missile.

Five of the seven missile types (SIDEWINDER, SPARROW, PHOENIX, HARM, and HARPOON) are presently still in production. This means that new missiles are still being built and introduced into the inventory throughout the year. The remaining two missiles, SHRIKE and WALLEYE are out of production, i.e. no more missiles are being added to the inventory.

The Navy has three intermediate level maintenance organizations responsible for the inspection and repair of the seven types of missiles in the inventory. The three organizations are Naval Weapons Stations (NWS). Two are located on the West Coast and one on the East Coast. They are situated in Concord, CA, Seal Beach, CA, and Yorktown, VA.

As intermediate level maintenance organizations, the Naval Weapons Stations are responsible for conducting testing of assembled missiles, corrosion control and repair, limited repairs to wiring and other components of the missile, and replacement of defective missile sections. In addition, the intermediate level unpacks the shipping and storage containers, inspects the missiles and missile sections and then repacks them after testing, cleaning, and repairs have been completed.

NWS Yorktown is the only one of the three intermediate level organizations which processes all types of missiles. NWS Fallbrook maintains SIDEWINDER, PHOENIX, WALLEYE, SHRIKE, and HARM, while NWS Concord maintains only SPARROW and HARPOON.

There are four reasons why a missile may be declared unuseable by the fleet and thus returned to the intermediate maintenance for repair. The first reason is Serviceable-In-Service-Time Expirations (SIST). SIST is defined as the length of time a missile can remain available for Fleet use before requiring an intermediate level maintenance inspection. Each time a missile undergoes intermediate level testing, a new maintenance due date (MDD) is assigned to the missile based on the SIST and service life.

The second reason a missile may be returned to the NWS is simple failure. This could include built-in-test failures, handling damage, or any other damage which is considered beyond the repair capability of the organizational level maintenance personnel.

The third reason a missile must be returned to intermediate maintenance is captive flight. Anytime a missile is taken out of its storage magazine on an aircraft carrier and flown on an aircraft but not fired, the missile must be returned to the intermediate level maintenance organization for inspection at the end of the current deployment. This is done regardless of whether or not the missile appears to be operating correctly. It must still be returned for test and cleaning.

The last reason a missile must be sent to the intermediate maintenance facility is for conversion. Conversion is the upgrading of a missile by modification or component replacement.

B. OBJECTIVES

The central objective of this thesis is the development of quantitative models which can be used to determine the optimal mix of missiles to induct for repair each quarter at each of the Navy's missile repair facilities. Three linear programming models have been developed. The first of the three linear programming models (LP1) minimizes the total cost of repair processing. It is subject to constraints dealing with asset readiness goals, facilities, and carcass availability.

The second model (LP2) minimizes the difference between actual and desired missile readiness and is subject to the same facility and carcass availability constraints. It also contains a constraint on the total missile repair budget.

The third model (LP3) enables the user to determine the necessary additional repair facilities required to obtain desired asset readiness if an infeasible solution is obtained from LP1.

These models have the capability of determining: the minimum cost mix with the unconstrained budget needed to attain readiness objectives; the optimal mix given a fixed budget and maintenance priorities between types of missiles in the missile inventory; and the additional facilities necessary to attain feasibility if an infeasible solution is obtained in the first model.

C. MODEL OBJECTIVES

There are three objectives to the models in this thesis. The primary objective is to determine whether a model can be developed to determine the optimal mix of missiles to induct for repair on a quarterly basis. Concurrent with the primary objective are two subsidiary objectives. The first is whether a model to describe the effects of budget changes on missile availability can be developed. The second subsidiary objective is whether this model can provide options on how to optimally respond to these budget changes.

D. APPLICATIONS OF THE MODELS

The three linear programming models developed in this thesis do not replace the missile repair workload planner, but instead provide him or her with a quantitative basis for planning. Depending on the situation, all three models could be used to aid in the scheduling of the inspection, testing, and repair of air launched missiles. For example, LP1 could be used to project future budget requirements by setting projected asset readiness objectives and having the model compute the minimum total processing cost. The resultant total would be the estimated budget requirement.

LP2 would be useful in maximizing the asset readiness posture of the missile inventory when operating under a budget constraint. The ability to set priorities between the missile systems is a particularly important feature of this model formulation.

The third model enables the workload planner to estimate long term requirements for additional test and repair facilities. Since missile inventories are forecasted to increase in size in the future, LP3 is an important tool which will help planners to estimate these requirements.

E. THESIS ORGANIZATION

The chapters in this thesis are organized around the problem solving cycle. Chapter II gives an overview of the procedures currently used to forecast and manage workload requirements. Chapter II also describes some of the problems associated with these current procedures. Chapter III describes the formulations of the three models. Chapter IV uses actual data from fiscal year 1986 to test the capabilities and limitations of the models. Chapter V validates the models by comparing model results using 1986 data with the actual missile repair plans for 1986 to see if the models would have improved the results. The final chapter contains conclusions and recommendations concerning the models and their use as a workload planning tool.

II. BACKGROUND OF THE PROBLEM

A. GENERAL BACKGROUND ON MISSILE LOGISTICS SUPPORT

NAVAIR CODE 418 is the command responsible for the logistics support of air launched missiles (ALMs). As such, it is responsible for the management of, and planning for, missile repair. This includes the forecasting of the budget needed, the determination of the numbers of missiles to repair, and the selection of the mix of missiles to be repaired at each repair station. The goal of this operation is to meet Asset Readiness Objectives (ARO) set by the Chief of Naval Operations (CNO) for each of the systems within the missile inventory.

ARO is defined as the percentage of missiles in the inventory that are classified as Ready-for-Issue (RFI). These ARO´s are set by the CNO for the fiscal year with regard to projected fleet requirements for each of the missile systems within the inventory. Calculation of ARO is obtained by dividing the number of projected RFI missiles needed by the total number of missiles in the inventory. This is done for each missile system within the inventory. Once the ARO has been set for each missile system by the CNO, NAVAIR CODE 418 must formulate a maintenance plan which meets these objectives.

This maintenance plan is known as the Air Launched Missile Maintenance-Workload Execution Plan (ALMM-WEP). The ALMM-WEP combines the projected fleet requirements with missile asset information from the Naval Supply System Command's (NAVSUP) Conventional Ammunition Integrated Management System (CAIMS) to develop a workload forecast for both intermediate level maintenance (ILM) and depot level maintenance (DLM).

Intermediate level maintenance consists of those functions normally performed by Naval Weapons Stations (NWS). These functions include inspection, disassembly, testing, minor repair, replacement of components, and incorporation of product improvement changes. Depot level maintenance consists of those functions normally performed by Naval Air Rework Facilities and commercial contractors. This work includes major repair and overhaul of ALM components and incorporation of certain product improvement changes.

The ALMM-WEP currently encompasses eight calendar-quarters. Using the information from the ALMM-WEP, Planners within NAVAIR CODE 418 can develop time-phased budget estimates of required manpower, facilities, equipment, materials, and funds for the annual and near-term ALM workload. To do this, it is necessary for the planner to "explode" the workload forecast into a workload package. This workload package contains information about what is to be done, by whom, for how long, on what material, and using what facilities, equipment and funds. The schedule and available resources are adjusted by means of repetitive calculations until a workable schedule consistent with available capacity is achieved.

B. STEPS IN THE WORKLOAD PROJECTION PROCESS

The following steps are derived from OPNAVINST 8600, the Naval Airborne Weapons Maintenance Program. They describe the procedure taken to ensure adequate rework maintenance is planned to maintain each missile inventory at the required level of readiness (ARO). These procedures are utilized by either NAVAIR CODE 418 planning personnel from the logistics management branch or by personnel from the Pacific Missile Test Center (PMTC), a field activity of NAVAIRSYSCOM, to formulate the workload projections for ALM repair. These projections are done annually and are updated at semiannual workload conferences.

Step 1: An analysis of the ALM inventory is performed for each year requiring a workload projection, to determine the end-of-year readiness posture that will result from known inventory adjustments. Table 2-1 shows the components of the analysis.

Beginning year assets are defined as the total quantity of units of a given missile system, categorized by serviceable or unserviceable condition.

TABLE 2-1. ALM INVENTORY ANALYSIS

Beginning Year Assets:	Serviceable	Unserviceable	Total
New Production Receipts:	+	N/A	+
Serviceable Transfers In:	+	N/A	+
Serviceable Transfers Out:	(-)	N/A	(-)
Unserviceable Transfers In:	N/A	+	+
Unserviceable Transfers Out:	N/A	(-)	(-)
Expenditures:	(-)	N/A	(-)
Fleet Fail Quantity:	(-)	+	N/A
Serviceable-In-service Time Expirations:	(-)	+	N/A
End-of-Year-Assets	Serviceable	Unserviceable	Total

New production receipts are the quantity of new missiles scheduled to be produced and delivered during the next fiscal year.

Serviceable transfers in, Serviceable transfers out, Unserviceable transfers in, and Unserviceable transfers out are defined as the number of missiles entering or leaving the missile inventory through conversion programs, replacement in kind programs, or Foreign Military Sales.

Expenditures are the number of missiles leaving the missile inventory due to destructive testing or firing.

The Fleet Fail Quantity is the expected rate at which missiles will be identified as early returns from the fleet, i.e. missiles which fail prior to their next scheduled preventive maintenance. Examples in this category include captive flight failures or handling damage.

Serviceable-In-Service-Time Expirations are defined as those missiles whose Serviceable-In-Service-Time (SIST) has expired. SIST is the length of time an asset can remain available for fleet use before requiring an intermediate level maintenaince inspection.

The "+" in the Table 2-1 refers to quantities that add to the category being calculated. The "-" in the figure refers to quantities that subtract from the category being calculated.

Step 2: Once the end-of year total assets are determined (Step 1), the serviceable assets required to meet the CNO readiness objectives are computed as follows:

$$A \times B = C$$

Where: A = ARO
B = End-of-year total assets
C = Serviceable assets required

Step 3: By comparing the serviceable assets required (Step 2) to the serviceable assets available at the end of the year without intermediate level maintenance (Step 1), the intermediate level workload is determined. The depot level workload is a fallout from the intermediate level. Any repair work that is beyond the scope of the intermediate level is turned over to the depot where more specialized maintenance can be accomplished. (See Step 4 below) Note that all assets available for repair are not scheduled for repair; only the quantity required to meet CNO readiness objectives are actually repaird.

$$C - D = E$$

Where: C = Serviceable assets required
D = Serviceable assets available (without intermediate level maintenance)
E = Intermediate level completions required

Step 4: The quantity of weapons requiring intermediate level maintenance is largely a result of Serviceable -In-Service-Time expirations, with a small factor added for Fleet failures and handling damage. However, not every missile tested results in a serviceable missile, (Step 3), due to component failures which are beyond intermediate level maintenance capability. These component failures comprise the depot level workload and are computed as follows:

$$F \times G = H$$

Where: F = Quantity of assets tested at the intermediate level
G = Failure rate for a specified component
H = Depot level maintenance workload for a specified component

Step 5: Once the intermediate and depot level requirements for preventive and corrective maintenance are forecasted, (Steps 1-4), requirements for the installation of missile modifications must be determined before the total maintenance requirement can be computed.

Requirements for modifications are based on approved configuration changes. The number of modifications which can be done is limited by the quantity of modification kits that will be produced and delivered during a given fiscal year and by the number of assets that will be available for modification at the intermediate and depot level facilities.

When available kits exceed the scheduled maintenance quantities, the number of excess kits is carried forward to the following year and the same comparison is performed. This process is continued until all modifications have been completed on a missile series.

Steps 1 thru 5 are performed for each model of missile in every missile system in the inventory. The calculations form a workload projection that is quite dynamic and must be kept current. Maintaining an accurate and up-to-date workload forecast is difficult due to changing fleet priorities. The missile repair budget is affected by fluctuations. As a result, frequent budget changes must be justified to examiners in the Navy and Department of Defense (DOD). At the present time, NAVAIR CODE 418 utilizes the workload projection steps described above to give them the most accurate and timely information on missile rework projections.

C. PROBLEMS WITH THE WORKLOAD PROJECTION PROCESS

As stated previously, the planners, either personnel from the logistics management branch of NAVAIR CODE 418, or from PMTC utilize the preceeding steps to formulate workload projections for ALM repair. This process is time-consuming and uses unrealistic estimates of actual numbers of assets within the missile inventories due to the time lags between actual changes in the missile inventories and the availability of this information to the workload planner. It also doesn´t allow NAVAIR CODE 418 to perform a cost analysis while being responsive to increases or decreases in the maintenance budget.

Changes in ARO for a missile series require individual adjustments to the workload for that series of missile. This analysis must be repeated for each of the 20 series. Then a cost must be obtained for each series, totalled to form an inventory workload package which stays within the total ALM maintenance budget. NAVAIR CODE 418 has no quick and efficient method to project budget needs, to react to changes in budget, or to project the overall optimal mix of missiles to be repaired each quarter that will maximize ARO while minimizing cost.

Another problem can be seen with the current planning process for missile modifications. In this process, the carrying cost of the modification kits is not considered. Nor is the military essentiality of the modification explicitly considered. If a modification were of an urgent or high priority, then consideration would have to be given to removing RFI missiles from deep storage and modifying as soon as modification kits are available. These factors would have an effect on a given quarter´s workload requirements and eventual budget, therefore they must be considered.

D. A PROBLEM SOLUTION USING LINEAR PROGRAMMING MODELS

This thesis attempts to solve these problems. Through the use of linear programming, a set of models that can determine the optimal mix of missiles to induct each quarter at the NWS provides NAVAIR CODE 418 with the means to make accurate workload projections and to be responsive to critical budget demands in a short period of time.

A set of three models has been developed to address these problems. The first model (LP1) attempts to determine the optimal mix of missiles to be repaired presuming the objective function is to minimize the total cost of repair across all missile systems. This formulation is constrained by missile readiness goals, intermediate maintenance facility availability, and missile carcass availability.

The second model attempts to determine an optimal mix of missiles to repair using the objective function of a weighted sum of the differences between actual missile readiness and the desired missile readiness for each system. This model is constrained by budget, intermediate maintenance facility availability, and missile carcass availability. This model also allows NAVAIR CODE 418 to prioritize the missile repair mix in order to account for changing demands from the fleet inputs that are received, along with changes in the CNO asset readiness objectives.

The third model (LP3) allows the user to determine the number of additional intermediate maintenance facilities that would be required to obtain asset readiness objectives if insufficient facilities are available to meet missile readiness objectives.

III. THEORETICAL FRAMEWORK AND MODEL DEVELOPMENT

A. GENERAL

Three linear programming models are used to determine the optimal mix of air launched missiles to be processed through the Naval Weapons Stations in a given time period. The first model (LP1) attempts to determine the optimal mix of missiles to be processed by minimizing the total cost of processing. This model is subject to constraints concerning missile asset readiness goals, facility availability, and asset availability.

If insufficient funding is available to achieve the missile asset readiness objectives given in the first model, LP1 will have no feasible solution and the user will need to run the second model (LP2). This model attempts to determine an optimal mix of missiles to be processed by minimizing the weighted sum of the differences between actual missile asset readiness and the desired missile asset readiness for each system. This model will be subject to budget, facility and missile carcass availability constraints.

A third model (LP3) is also described, LP3 allows the user to determine the number of additional processing facilities which would be required to obtain feasibility if an infeasible solution is obtained from LP1. This would occur in the event that the desired asset readiness goals could not be attained by the end of the given time period, due to the facility constraints.

B. DEFINITIONS

The following variables are used in LP1:

C_t = The total cost to process all of the air launched missiles in a time period.

C_{ijk} = The average cost to process the kth missile version of the ith missile system at the jth Naval Weapons Station.

X_{ijk} = The number of missiles of system i, version k, to be processed at Naval Weapons Station j in a time period.

T_{ik} = The total number of missiles of system i, version k, expected to be in the inventory at the end of a given time period. This is equal to the expected number of missiles in the inventory at the beginning of the time period plus the number of new production missiles, minus the number of missiles fired during the time period.

U_{ijk} = The number of Not Ready for Issue (NRFI) missiles of system i, version k, at Naval Weapons Station j, at the beginning of a given time period.

I_{ijk} = The expected number of missile carcasses of system i, version k, to arrive at Naval Weapon Station j during a given time period.

A_{ik} = The desired asset readiness percentage for missile system i, version k. This is defined as the number of Ready for Issue (RFI) missiles divided by the number of total missiles of system i, version k.

N_{ij} = The number of repair channels for missile system i at the jth Naval Weapons Station.

D_{eg} = The number of equivalent missile processing days available in the time period. For example, there are 180 equivalent missile processing days available ($D_{eg} = 20 \times 3 \times 3 = 180$) in a sample time period of one calendar quarter, assuming the work proceeds 5 days per week, 4 weeks per months using 3 shifts per day.

W_{ij} = The maximum missile processing rate (missiles/day) per repair channel for missile system i at Naval Weapons Station j.

M_i = The number of missile versions of the ith missile system.

The decision variables of LP1 are designated X_{ijk} and represent the number of missiles of system i, version k, to be processed at Naval Weapons Station j during a given time period.

C. FORMULATION OF LP1

The objective function for LP1 (EQ. 1) defines the total cost, C_t, as a function of the repair/processing costs per missile (by version) and the decision variables, X_{ijk}.

$$\text{EQ. (1)} \quad \text{MIN } C_T = \sum_{j=1}^{3} \sum_{i=i}^{7} \sum_{k=i}^{Mi} C_{ijk} X_{ijk}$$

There are seven missile systems (SHRIKE, HARM, HARPOON, PHOENIX, SIDEWINDER, SPARROW, and WALLEYE) currently modeled in LP1. The objective equation increments i from 1 to 7, j from 1 to 3, and k from 1 to M_i to allow for different missile versions which entail different repair/processing costs. For example, X_{123} is the number of missiles of the third version of missile system 1 to process at NWS 2 during a given time period. There are three Naval Weapons Stations (Fallbrook, Yorktown, and Concord) used in the model.

Three types of constraints are used in LP1. The first constraint deals with the asset readiness objective required of each version. The second constraint is due to the limited testing facilities available at the NWS. The third constraint deals with the availability of the assets to process at the individual NWS´s.

The asset readiness constraints for LP1 are of the type shown in equation (2):

$$\text{EQ. (2)} \quad \sum_{j=1}^{3} X_{ijk} \geq T_{ik}(A_{ik}-1) + \sum_{j=1}^{3} U_{ijk} + I_{ijk} \quad \text{For all } i,k$$

There are a total of nineteen of these constraint equations. A separate constraint equation must be written for each missile version. The left side of the inequality represents the total number of missiles of system i, version k, required to be processed in a given time period.

The right hand side of the inequality can be rearranged into the two components shown below to better illustrate the meaning of the constraint.

a. $T_{ik}(1-A_{ik})$ = The acceptable number of NRFI missiles of system i, version k, at the end of a given time period.

b. $(U_{ijk}+I_{ijk})$ = The repair load (or number of NRFI missiles of system i, version k, available to repair) during a given time period.

Therefore, in equation (3) it can be seen that the number of missiles of system i, version k, to be processed, must be greater than the repair load minus the acceptable number of NRFI missiles.

EQ. (3) $$\sum_{j=1}^{3} X_{ijk} \geq \sum_{j=1}^{3} (U_{ijk} + I_{ijk}) - T_{ik}(1-A_{ik})$$

The second set of constraints for LP1 deals with the facility limitations and is formulated in equations (4) and (5).

EQ. (4) $$\sum_{k=1}^{M_i} [W_{ij}]^{-1} X_{ijk} \leq D_{eg} N_{ij} \quad \text{For all } i,j$$

Equation (4) sets the maximum number of missiles of system i that can be processed at NWS j during a given time period. These constraint equations are independent of the missile version because all missiles of a given system have approximately equal processing time. This type of constraint leads to a total of 21 (7 x 3) constraint equations, including one equation for each combination of missile system and NWS. However, some of these constraints are not required because not all missile systems are processed at each NWS.

An exception to this constraint formula must be made for NWS Yorktown where two missile systems are tested in the same repair channel (test cell) and both systems cannot be tested simultaneously. SHRIKE and HARM are tested in one test cell and HARPOON and WALLEYE are tested in one test cell. The constraint formula for this special condition is given in equation (5). Equation (5) would result in two constraint equations, one for each test cell. Therefore, this second set of constraints requires a total of 12 equations.

EQ. (5) $$\sum_{k=1}^{M_i} \left[W_{ij}\right]^{-1} X_{ijk} \leq D_{eg}$$

The third set of constraints concerns missile carcass availability. These constraints are required to ensure that the solution given does not allow for more missiles to be processed at a NWS than missile carcasses are available. Equation (6) gives the formula for this asset availability constraint. This set of constraints results in 38 constraint equations.

EQ. (6) $X_{ijk} \leq U_{ijk} + I_{ijk}$ For all i,j,k

D. FORMULATION OF LP2

The variables used in LP2 have the same meaning as those defined for LP1, with the addition of the following variables:

K_{ik} = A constant supplied by the user which represents the priority on missile system i, version k. If no systems have a priority, K_{ik} can be set equal to 1, for all i and k.

R_{ik} = The actual asset readiness ratio of missile system i, version k. This is defined as the number of RFI missiles divided by the number of total missiles.

B = The total budget allocated for processing missiles for a given time period.

The decision variables for LP2 are the same as the decision variables for LP1. They represent the number of missiles of system i, version k, to process at NWS j during a given time period.

The objective equation for LP2 attempts to minimize the difference between the desired missile asset readiness and the actual missile asset readiness. Equation (7) shows the fundamental objective function.

$$\text{EQ. (7)} \qquad \text{Min} \sum_{i=1}^{7} \sum_{k=1}^{M_i} K_{ik}\left(A_{ik}-R_{ik}\right)^2$$

By minimizing the square of this difference, the algorithm will give the mix of missiles required to be processed which will cause the actual asset readiness to approach A_i as close as possible. Using the definition for R_{ik} and a little algebra, equation (7) can be written as shown in equation (8).

$$\text{EQ. (8)} \qquad \text{MIN} \sum_{i=1}^{7} \sum_{k=1}^{M_i} K_{ik}\left(A_{ik}-1+\sum_{j=1}^{3} \frac{U_{ijk}+I_{ijk}-X_{ijk}}{T_{ik}}\right)^2$$

It can then be shown that minimizing equation (8) is the same as minimizing equation (9) which is the form of the objective function we will use for LP2. We can eliminate the square by adding a third constraint equation which is discussed later. See Appendix A for a detailed explanation.

$$\text{EQ. (9)} \qquad \text{Min} \sum_{i=1}^{7} \sum_{k=1}^{M_i} - {}^{Kik}\!/_{Tik} \sum_{j=1}^{3} X_{ijk}$$

There are four types of constraints used in LP2. The first constraint is required to account for limited funding. The second type of constraint is the same type of facility constraint as was used in LP1. The third constraint equation allows us to discard the square from the original objective equation. This third constraint limits the solution to asset readiness objectives such that once a missile system has reached its ARO, the algorithm will refrain from repairing any more missiles from that particular system. The fourth constraint is identical to the asset availability constraint used in LP1.

The first constraint is shown in equation (10):

EQ. (10) $$\sum_{j=1}^{3} \sum_{i=1}^{7} \sum_{k=1}^{M_i} C_{ijk} X_{ijk} \leq B$$

The second type of constraint is shown again in equations (11) and (12) and is identical to equations (4) and (5) for LP1.

EQ. (11) $$\sum_{k=1}^{M_i} \left[W_{ij}\right]^{-1} X_{ijk} \leq D_{eg} N_{ij} \quad \text{For all } i,j$$

EQ. (12) $$\sum_{k=1}^{M_i} \left[W_{ij}\right]^{-1} X_{ijk} \leq D_{eg}$$

The third constraint is shown in equation (13).

EQ. (13) $$\sum_{j=1}^{3} X_{ijk} \leq T_{ik}\left(A_{ik}-1\right) + \sum_{j=1}^{3} U_{ijk}+I_{ijk} \quad \text{For all } i,\ j,\ k$$

The fourth type of constraint is identical to the missile carcass availability constraints of LP1 shown in equation (6).

E. FORMULATION OF LP3

The variables used in LP3 are the same as those used in LP1 and LP2, in addition to the following:

F_{ij} = The cost of one additional repair channel for the ith missile system at the jth NWS.

Y_{ij} = The optimal number of additional repair channels for the ith missile system at the jth NWS required in order to meet the ARO's.

The objective function for LP3 is similar to that used in LP1, with the addition of the repair channel variables. The objective function for LP3 (EQ. 14) defines total cost as a function of the processing cost for each missile system and the cost of additional repair channels.

EQ. (14) $$MIN\ C_T = \sum_{j=1}^{3} \sum_{i=1}^{7} \sum_{k=1}^{M_i} C_{ijk}X_{ijk} + \sum_{j=1}^{3} \sum_{i=1}^{7} F_{ij}Y_{ij}$$

Since there are seven missile systems, each of which requires a single type of repair channel, the second part of the objective function only needs to be summed over i = 1 to 7 and j = 1 to 3.

However, since there are various versions of these missiles with each version having a different processing cost, the first part of the objective equation must be summed over k = 1 to M_i.

The constraints for LP3 are similar to the constraints used in LP1. The first constraint will make the solution meet asset readiness ratio constraints. The second constraint is the facility constraint and takes into account the additional facilities added by LP3.

The first constraint is identical to equation (7) of LP1 and is repeated in equation (15).

EQ. (15) $$\sum_{j=1}^{3} X_{ijk} \geq T_{ik} A_{ik}^{-1} + \sum_{j=1}^{3} U_{ijk} + I_{ijk} \quad \text{For all } i,k$$

The second type of constraint for LP3 is similar to the facility constraints in LP1 and is shown in equation (16). Equation (17) is the equivalent form required for the linear programming model.

EQ. (16) $$\sum_{k=1}^{M_i} \left[W_{ij}\right]^{-1} X_{ijk} \leq D_{eg}\left(N_{ij}+Y_{ij}\right) \quad \text{For all } i,j$$

EQ.(17) $$\sum_{k=1}^{M_i} \left[W_{ij}\right]^{-1} X_{ijk} - D_{eg}Y_{ij} \leq D_{eg}N_{ij} \quad \text{For all } i,j$$

An exception must be made in LP3 just as was done in LP1 for NWS Yorktown in which some processing cells are shared by two missile systems. For these systems the second constraint would be similar to equation (5) of LP1, and is shown in equation (18).

EQ. (18) $$\sum_{k=1}^{M_i} \left[W_{ij}\right]^{-1} X_{ijk} - \sum_{i=1}^{2} D_{eg} Y_{ij} \leq D_{eg}$$

IV. INPUT DATA AND MODEL OPTIMIZATION

A. GENERAL

All three models were applied using data from fiscal year 1986 to determine the optimal mix of missiles to process during the quarter beginning 1 January 1986 and ending 31 March 1986. The first model (LP1) used this data to determine the mix of missiles to process which would minimize the total cost, subject to missile asset readiness and processing facility constraints. Estimates of some data elements were not available.[1] In these cases, actual data was used instead of planned data. The actual source of each of the input variables is described below. Details on the operational use of the LINDO program at the Naval Postgraduate School are given in Appendix B.

B. LP1 INPUT/OUTPUT DATA

The input data required by LP1 is C_{ijk}, T_{ik}, U_{ijk}, I_{ijk}, and A_{ik} as defined in Chapter III. The cost to process the kth version of the ith missile system at the jth Naval Weapons Station (C_{ijk}) was taken from the Fiscal Year 1986 Project Directive based on planned unit costs.

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[1] We attempted to use only data which was in the form it would have been in prior to 1 Jan 86.

Table 4-1 shows the missile systems used in the model and their corresponding input variables.[2]

The number of NRFI missiles (U_{ijk}) of system i, version k, at NWS j, at the beginning of the quarter was obtained from a Conventional Ammunition and Inventory Management System (CAIMS) report dated 4 January 1986. The report gives a snapshot inventory description on this date. The user of this model would have to use projected information from sources such as the Inventory Projection Model (IPM) to obtain this element of data.

The expected number of missiles of system i, version k, to arrive at NWS j during the given quarter, I_{ijk}, was obtained from the planned number of units of inducted missiles from the FY 1986 Project Directive. The user of this model would have to use projected information from sources such as the Inventory Projection Model to obtain this element of data.

The total number of missiles (T_{ik}) of system i, version k, expected to be in the inventory at the end of the given quarter was taken from the CAIMS report for 1 April 1986. The user of the model would have to use projected information from sources such as the Inventory Projection Model to obtain this data element.

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[2] T_{ik} and A_{ik} were not included in Table 1 in order to avoid use of any classified information in the thesis.

TABLE 4-1. LP1 INPUT VARIABLES

Missile System	i	NWS	j	Missile Version	k	C_{ijk} ($/msl)	U_{ijk} (units)	I_{ijk} (units)
SIDEWINDER	1	YT	1	AIM-9H	1	2031	275	23
"	1	SB	2	"	1	1688	275	23
"	1	YT	1	AIM-9L	2	1624	175	67
"	1	SB	2	"	2	1314	175	67
"	1	YT	1	AIM-9M	3	1502	95	103
"	1	SB	2	"	3	1125	95	103
"	1	YT	1	9M UPGRADE	4	377	95	103
"	1	SB	2	"	4	417	95	103
SPARROW	2	YT	1	AIM-7E	1	3080	13	10
"	2	CC	3	"	1	4981	13	10
"	2	YT	1	AIM-7F	2	1659	95	65
"	2	CC	3	"	2	1477	95	65
"	2	YT	1	BPD	3	2077	68	23
"	2	CC	3	"	3	2023	68	23
"	2	YT	1	IPD	4	1732	120	42
"	2	CC	3	"	4	1615	120	42
"	2	YT	1	AIM-7M	5	1508	43	57
"	2	CC	3	"	5	1947	43	57
"	2	YT	1	RIM-7M	6	3505	5	8
"	2	CC	3	"	6	5073	5	8
WALLEYE	3	YT	1	I	1	1219	247	48
"	3	SB	2	"	1	1270	247	48
"	3	YT	1	I ER/DL	2	1515	33	17
"	3	SB	2	"	2	1749	33	17
"	3	YT	1	DPSK	3	2834	8	18
"	3	SB	2	"	3	1177	8	18
"	3	YT	1	II ER/DL	4	1869	93	32
"	3	SB	2	"	4	1401	93	32
SHRIKE	4	YT	1	AGM-45	1	378	335	175
"	4	SB	2	"	1	934	335	175
PHOENIX	5	YT	1	AIM-54	1	1521	155	168
"	5	SB	2	"	1	1240	155	168
HARM	6	YT	1	AGM-88	1	2094	30	17
"	6	SB	2	"	1	2393	30	17

TABLE 4-1. LP1 INPUT VARIABLES (Continued)

Missile System	i	NWS	j	Missile Version	k	C_{ijk} ($/msl)	U_{ijk} (units)	I_{ijk} (units)
HARPOON	7	YT	1	(A)	1	6920	23	18
"	7	CC	3	"	1	4628	23	18
"	7	YT	1	(R)	2	7233	60	31
"	7	CC	3	"	2	6292	60	31
"	7	YT	1	(U)	3	11532	70	12
"	7	CC	3	"	3	11168	70	12

C_{ijk}- average cost to process the kth missile version of the ith missile system at the jth NWS.

U_{ijk}- number of NRFI missiles of system i, version k, at NWS j, at the start of the given time period.

I_{ijk}- expected number of missiles of system i, version k, to arrive at NWS j during a given time period.

The desired asset readiness objective (ARO) (A_{ik}) for version k of missile system i was obtained from Volume 1 of the Weapons Armament Asset Readiness report of October 1986.

Table 4-2 shows the data used to determine the facility constraints for LP1. The maximum missile processing rate (W_{ij}) (missiles/day) per channel for missile system i, at NWS j was obtained from interviews with appropriate personnel at each NWS.

The user of this model could use the data supplied by NWS personnel (which we feel is realistic), or could obtain W_{ij} from the Industrial Processing Guide. The Industrial Processing Guide sets the standard missile processing rates that the NWS´s should achieve. The values used for W_{ij} assume three shifts per day are operated at each NWS five days a week, since this constraint is setting the absolute maximum on the missile processing rate. This figure also represents an average, which assumes normal failure/retest rates and no unusual occurrences. The sample data formulation of LP1 is shown in Appendix C.

The output for LP1 using this data is shown in Table 4-3. The minimum value of the objective function was $5,070,262.00, which represents the actual total cost of processing the mix of missiles for the 2nd quarter of FY 1986.

TABLE 4-2. MISSILE PROCESSING RATES

MISSILE SYSTEM	i	NWS	j	(Missiles/ day) W_{ij}	$[W_{ij}]^{-1}$*
SIDEWINDER	1	YT	1	24	.042
"	1	SB	2	36	.028
SPARROW	2	YT	1	21	.048
"	2	CC	3	24	.042
WALLEYE	3	YT	1	18	.056
"	3	SB	2	15	.067
SHRIKE	4	YT	1	21	.048
"	4	SB	2	24	.042
PHOENIX	5	YT	1	12	.083
"	5	SB	2	12	.083
HARM	6	YT	1	6	.167
"	6	SB	2	9	.111
HARPOON	7	YT	1	6	.167
"	7	CC	3	6	.167

* Figures used for $[W_{ijk}]^{-1}$ were rounded to three decimal places for display, actual figures used in the model were carried to 8 digits.

TABLE 4-3. LP1 OUTPUT DATA

Missile System	i	NWS	j	Missile Version	k	X_{ijk}
SIDEWINDER	1	YT	1	AIM-9H	1	69
"	1	SB	2	"	1	298
"	1	YT	1	AIM-9L	2	50
"	1	SB	2	"	2	241
"	1	YT	1	AIM-9M	3	0
"	1	SB	2	"	3	0
"	1	YT	1	9M UPGRADE	4	291
"	1	SB	2	"	4	0
SPARROW	2	YT	1	AIM-7E	1	23
"	2	CC	3	"	1	17
"	2	YT	1	AIM-7F	2	0
"	2	CC	3	"	2	124
"	2	YT	1	BPD	3	16
"	2	CC	3	"	3	91
"	2	YT	1	IPD	4	40
"	2	CC	3	"	4	161
"	2	YT	1	AIM-7M	5	42
"	2	CC	3	"	5	0
"	2	YT	1	RIM-7M	6	0
"	2	CC	3	"	6	0
WALLEYE	3	YT	1	I	1	345
"	3	SB	2	"	1	98
"	3	YT	1	I ER/DL	2	47
"	3	SB	2	"	2	0
"	3	YT	1	DPSK	3	0
"	3	SB	2	"	3	0
"	3	YT	1	II ER/DL	4	6
"	3	SB	2	"	4	125
SHRIKE	4	YT	1	AGM-45	1	387
"	4	SB	2	"	1	0
PHOENIX	5	YT	1	AIM-54	1	42
"	5	SB	2	"	1	322
HARM	6	YT	1	AGM-88	1	33
"	6	SB	2	"	1	0
HARPOON	7	YT	1	(A)	1	0
"	7	CC	3	"	1	0
"	7	YT	1	(R)	2	0
"	7	CC	3	"	2	80
"	7	YT	1	(U)	3	0
"	7	CC	3	"	3	71

C. LP2 INPUT/OUTPUT DATA

The objective function for LP2 was given in Equation (8) of Chapter III. LP2 was a minimization problem with negative priority coefficients. In order to simplify the formulation, LP2 was run as a maximization problem using positive priority coefficients in the objective function.

In the set up of LP2 for model validation, K_{ik} was selected to be the same for all missile systems. This implies that no system had a priority over any other system. Any value of K_{ik} could have been selected, but, for simplicity equal priorities were assumed. The objective function coefficients are given in Table 4-4. The values for K_{ik} and T_{ik} are not given in order to avoid using classified information in the thesis.

LP2 was run using the same sample data that was used for LP1. The major difference was that there was a budget constraint of $3,580,701 applied in LP2. This was the actual total missile processing cost for the sample time period in 1986.

The first constraint in LP2 is identical to the objective function for LP1. However, it is stated as a constraint, i.e. that this total cost for the sample time period must be less than $3,580,701. The second set of constraints are the repair facility constraints. They are identical to the facility constraints of LP1. The third set of constraints for LP2 are similar to the first set of constraints for LP1.

TABLE 4-4. LP2 OBJECTIVE FUNCTION COEFFICIENTS

MISSILE SYSTEM	i	MISSILE VERSION	k	K_{ik}/T_{ik} *
SIDEWINDER	1	AIM-9H	1	.062
"	1	AIM-9L	2	.073
"	1	AIM-9M	3	.028
"	1	9M UPGRADE	4	.028
SPARROW	2	AIM-7E	1	3.85
"	2	AIM-7F	2	.072
"	2	BPD	3	.214
"	2	IPD	4	.127
"	2	AIM-7M	5	.089
"	2	RIM-7M	6	.213
WALLEYE	3	I	1	.057
"	3	I ER/DL	2	.269
"	3	DPSK	3	.129
"	3	I ER/DL	4	.118
SHRIKE	4	AGM-45	1	.022
PHOENIX	5	AIM-54	1	.050
HARM	6	AGM-88	1	.231
HARPOON	7	(A)	1	.160
"	7	(R)	2	.136
"	7	(U)	3	.151

*K_{ik}/T_{ik} figures were rounded to 3 digits for display, actual figures were calculated to 8 digits.

These constraints are necessary to eliminate the square in the objective function given by Equation (8) of Chapter III (see Appendix A).

These constraints require that once the number of missiles needed to meet the ARO have been assigned to a specific variable, the model will not continue assigning missiles to this decision variable. The fourth set of constraints is identical to the missile carcass availability constraints of LP1.

The problem formulation for LP2 is shown in Appendix D with the corresponding output shown in Table 4-5.

D. LP3 INPUT/OUTPUT DATA

LP3 was used to show how many additional maintenance channels must be added if an infeasible solution is obtained in LP1. This would occur if facility constraints prohibited the processing of enough missiles to achieve the ARO´s.

Since LP3 is not used unless LP1 is infeasible, a set of sample data was created which yields an infeasible LP1. The original sample data for LP1 was modified in two respects to achieve this goal. First, the right hand side of the ARO constraints in LP3 were given values which were twice the value of the right hand side of the ARO constraints in LP1. Second, the right hand side of each facility constraint was reduced by a factor of 6.

TABLE 4-5. LP2 OUTPUT DATA

Missile System	i	NWS	j	Missile Version	k	X_{ijk}
SIDEWINDER	1	YT	1	AIM-9H	1	69
"	1	SB	2	"	1	298
"	1	YT	1	AIM-9L	2	50
"	1	SB	2	"	2	241
"	1	YT	1	AIM-9M	3	0
"	1	SB	2	"	3	0
"	1	YT	1	9M UPGRADE	4	291
"	1	SB	2	"	4	0
SPARROW	2	YT	1	AIM-7E	1	23
"	2	CC	3	"	1	17
"	2	YT	1	AIM-7F	2	0
"	2	CC	3	"	2	124
"	2	YT	1	BPD	3	16
"	2	CC	3	"	3	91
"	2	YT	1	IPD	4	40
"	2	CC	3	"	4	161
"	2	YT	1	AIM-7M	5	42
"	2	CC	3	"	5	0
"	2	YT	1	RIM-7M	6	0
"	2	CC	3	"	6	0
WALLEYE	3	YT	1	I	1	345
"	3	SB	2	"	1	98
"	3	YT	1	I ER/DL	2	47
"	3	SB	2	"	2	0
"	3	YT	1	DPSK	3	0
"	3	SB	2	"	3	0
"	3	YT	1	II ER/DL	4	6
"	3	SB	2	"	4	125
SHRIKE	4	YT	1	AGM-45	1	167
"	4	SB	2	"	1	0
PHOENIX	5	YT	1	AIM-54	1	42
"	5	SB	2	"	1	322
HARM	6	YT	1	AGM-88	1	33
"	6	SB	2	"	1	0
HARPOON	7	YT	1	(A)	1	0
"	7	CC	3	"	1	0
"	7	YT	1	(R)	2	0
"	7	CC	3	"	2	0
"	7	YT	1	(U)	3	0
"	7	CC	3	"	3	0

The objective function for LP3 is identical to that of LP1 with the addition of the new decision variables, Y_{ij}. These variables represent the number of additional repair channels required for the ith missile system at the jth NWS to meet the ARO constraints. The coefficients for these variables, F_{ik}, the cost of one additional repair channel for the ith missile system at the jth NWS, are shown in Table 4-6. These unit costs were estimated in order to show how the model would work. They were also assumed to be independent of location.

There are two sets of constraints for LP3. The first set of constraints is identical to the asset readiness constraints of LP1. The second set of constraints is similar to the facility constraints of LP1, except that they include the capacity added by the additional repair channels, Y_{ij}.

The problem formulation for LP3 is shown in Appendix E. Because of the limitations of the linear programming software (LINDO) used to optimize the models, an INTEGER command was added to the program such that the only possible values for Y_{ij} were 1 or 0. This means the model, in its present implementation, would never recommend that 2 or more repair channels be added at any NWS.

The output for the optimal mix of missiles given by LP3 is shown in Table 4-7. The output for the number of additional repair channels along with their cost coefficients is given in Table 4-6.

TABLE 4-6. LP3 FACILITY MIX OUTPUT DATA

MISSILE SYSTEM	i	NWS	j	F_{ij}	Y_{ij}
SIDEWINDER	1	YT	1	500	0.00
"	1	SB	2	500	1.00
SPARROW	2	YT	1	1500	0.00
"	2	CC	3	1500	1.00
WALLEYE	3	YT	1	500	0.00
"	3	SB	2	500	0.00
SHRIKE	4	YT	1	50	1.00
"	4	SB	2	50	0.00
PHOENIX	5	YT	1	3000	0.00
"	5	SB	2	3000	1.00
HARM	6	YT	1	2000	0.00
"	6	SB	2	2000	0.00
HARPOON	7	YT	1	3000	0.00
"	7	CC	3	3000	1.00

TABLE 4-7. LP3 MISSILE MIX OUTPUT DATA

Missile System	i	NWS	j	Missile Version	k	X_{ijk}
SIDEWINDER	1	YT	1	AIM-9H	1	0
"	1	SB	2	"	1	734
"	1	YT	1	AIM-9L	2	0
"	1	SB	2	"	2	582
"	1	YT	1	AIM-9M	3	0
"	1	SB	2	"	3	0
"	1	YT	1	9M UPGRADE	4	582
"	1	SB	1	"	1	0
SPARROW	2	YT	1	AIM-7E	1	80
"	2	CC	3	"	1	0
"	2	YT	1	AIM-7F	2	0
"	2	CC	3	"	2	248
"	2	YT	1	BPD	3	0
"	2	CC	3	"	3	214
"	2	YT	1	IPD	4	0
"	2	CC	3	"	4	402
"	2	YT	1	AIM-7M	5	84
"	2	CC	3	"	5	0
"	2	YT	1	RIM-7M	6	100
"	2	CC	3	"	6	0
WALLEYE	3	YT	1	I	1	886
"	3	SB	2	"	1	0
"	3	YT	1	I ER/DL	2	94
"	3	SB	2	"	2	0
"	3	YT	1	DPSK	3	0
"	3	SB	2	"	3	100
"	3	YT	1	II ER/DL	4	0
"	3	SB	2	"	4	262
SHRIKE	4	YT	1	AGM-45	1	774
"	4	SB	2	"	1	0
PHOENIX	5	YT	1	AIM-54	1	0
"	5	SB	2	"	1	724
HARM	6	YT	1	AGM-88	1	66
"	6	SB	2	"	1	0
HARPOON	7	YT	1	(A)	1	0
"	7	CC	3	"	1	100
"	7	YT	1	(R)	2	0
"	7	CC	3	"	2	160
"	7	YT	1	(U)	3	42
"	7	CC	3	"	3	100

V. DATA VALIDATION

A. LP1 OUTPUT

The output for LP1 was shown in the previous chapter in Table 4-3. The most noticeable characteristic of this data is the number of zeroes in the X_{ijk} column. For instance this output implies no missiles of versions AIM-9M, RIM-7M, WALLEYE DPSK, and HARPOON (A) should be processed this quarter. The reason for this is that the input data has shown that these missile versions are currently, and are projected to be, meeting their ARO´s at the end of the given quarter.

Another characterisitc of this data is the frequency which the model indicates that all missiles of a particular version should be processed at one NWS. This occurs with the 9M-UPGRADE, AIM-7F, AIM-7M, WALLEYE ER/DL, SHRIKE, HARM, and HARPOON. If the processing cost for a particular missile version is lower at one NWS, the model will process the maximum possible number of missiles at that NWS before it processes any at another NWS.

One weakness in LP1 is that it assumes that the processing cost per missile is independent of the number of missiles processed, that is, it costs the same to process the first missile as it costs to process the nth missile. The model does not allow for the fixed costs of setting up the test equipment and preparing the test cell. This shows how sensitive the model is to this processing cost, C_{ijk}. If one NWS´s cost is only one dollar lower, the model will assign all missiles to be processed at that NWS until it´s capacity is reached or all missiles are processed. The workload planner using the model would have to observe this and perhaps deviate from the LP1 solution if, for external reasons, it was necessary to balance the workload among NWS´s.

Since LP1 was unconstrained by budget limitations, the objective function value, (the cost to process this mix of missiles), was $5,070,262. This is about 40% higher than the normal quarterly maintenance budget of about $3,600,000. In order to obtain a more affordable solution with this sample data, the user would have to use LP2.

B. LP2 OUTPUT

Using the same sample data and LP2, a budget constraint of $3,580,701 was represented. This was the actual missile processing cost for the quarter, therefore allowing a logical comparison of the output with the actual data. The output for LP2 was given in Table 4-5.

The first significant result made from this data is the increased number of zeroes in the X_{ijk} column. Basically this occurs because we now have less money to process missiles. In comparing the output of LP2 to that of LP1, it can be seen that many of the systems are not going to reach their ARO´s by the end of the quarter.

In the formulation of LP2, K_{ik} was set equal for each missile system. In reality the user would have to set values of K_{ik} depending on the relative priority of each system.

LP2 was solved again after it was modified to assign a priority to the HARPOON system. This was accomplished by increasing the value of K_{ik} to 10,000 for all versions of the HARPOON missile. The output for this modified data is given in Table 5-1.

As expected, the model has assigned the maximum number of HARPOON to be processed within the constraints. In order to meet the budget constraints, the model reduced the number of SIDEWINDER 9M, and SHRIKE to be processed.

If there are no missile systems with a priority, the model will assign the missile system with the lowest total inventory to be processed first. This occurs because LP2 is attempting to maximize asset readiness given the budget constraint. If one missile system is currently 20% below it´s ARO and another missile system is 1% below it´s ARO, the model will assign missiles to this latter system to be processed if this system has a lower total inventory, T_{ik}, and both systems have the same priority, K_{ik}. If the user objects to this procedure, the relative values of K_{ik} can be adjusted accordingly.

TABLE 5-1. LP2 OUTPUT DATA USING A PRIORITY ON THE HARPOON SYSTEM

Missile System	i	NWS	j	Missile Version	k	X_{ijk}
SIDEWINDER	1	YT	1	AIM-9H	1	0
"	1	SB	2	"	1	0
"	1	YT	1	AIM-9L	2	50
"	1	SB	2	"	2	241
"	1	YT	1	AIM-9M	3	0
"	1	SB	2	"	3	0
"	1	YT	1	9M UPGRADE	4	291
"	1	SB	2	"	4	0
SPARROW	2	YT	1	AIM-7E	1	23
"	2	CC	3	"	1	17
"	2	YT	1	AIM-7F	2	0
"	2	CC	3	"	2	124
"	2	YT	1	BPD	3	16
"	2	CC	3	"	3	91
"	2	YT	1	IPD	4	40
"	2	CC	3	"	4	161
"	2	YT	1	AIM-7M	5	42
"	2	CC	3	"	5	0
"	2	YT	1	RIM-7M	6	0
"	2	CC	3	"	6	0
WALLEYE	3	YT	1	I	1	345
"	3	SB	2	"	1	64
"	3	YT	1	I ER/DL	2	47
"	3	SB	2	"	2	0
"	3	YT	1	DPSK	3	0
"	3	SB	2	"	3	0
"	3	YT	1	II ER/DL	4	6
"	3	SB	2	"	4	125
SHRIKE	4	YT	1	AGM-45	1	0
"	4	SB	2	"	1	0
PHOENIX	5	YT	1	AIM-54	1	0
"	5	SB	2	"	1	0
HARM	6	YT	1	AGM-88	1	33
"	6	SB	2	"	1	0
HARPOON	7	YT	1	(A)	1	0
"	7	CC	3	"	1	0
"	7	YT	1	(R)	2	0
"	7	CC	3	"	2	80
"	7	YT	1	(U)	3	0
"	7	CC	3	"	3	71

C. LP3 OUTPUT

The output for LP3 is shown in Table 4-6 and 4-7. The sample data used in LP1 and LP2 was altered for use in LP3 to show how LP3 would be used to determine the number of additional repair channels required to meet asset readiness objectives. LP3 would be required if the solution to LP1 is infeasible, and if the user needed to know the optimal number of repair channels to add.

To obtain a realistic example of the use of LP3, the missile load requirements were doubled and the facility processing capacities were reduced by 1/6. The most important item of input data is the cost of an additional repair channel for missile system i at each NWS j (F_{ij}). In the sample run, these values were based on rough estimates. In actual use, the user would need to calculate the life-cycle cost for each additional repair channel. LP3 would be most useful if the timeframe were extended, and the missile load requirements were obtained from the Inventory Projection Model. LP3 could then be used to help determine the optimal number of repair channels to add within the next seven years.[3] The objective function value for LP3 using the sample data was $10,904,438. This value actually has little meaning since the facility figures were scaled.

---

[3]The inventory projection model provides forecasts out to 7 years in the future.

The facility cost figures values were scaled because only the relative unit costs of the facilities are relevant and it allows the use of smaller numbers. The user could calculate the actual cost by multiplying the scale factor by the facility unit costs and adjusting this value.

LP3 could be run with carcass availability constraints similar to the ones used in LP1. In order to get an output to show the usefulness of LP3, the current formulation assumes that all NRFI missiles are available for maintenance. This output is shown in Table 4-7.

The output for the optimal missile mix in LP3 is shown in Table 4-6. Since this output was based on fictitious input, the X_{ijk} values obtained cannot be compared with the other models' output. The main function of LP3 would be to determine the optimal number and location of additional repair channels.

D. COMPARISON OF THE MODEL WITH ACTUAL DATA

A comparison between the missile mixes recommended by LP1, LP2 and the actual mix is shown in Table 5-2. There are numerous implications of the differences shown in the table. There are two main reasons for a possible discrepancy between the output of LP1, LP2 and LP3 and the actual missile mix. The first reason would be that actual values were used for T_{ik} and workload projections for I_{ijk}. These values can and should be obtained from the Inventory Projection Model.

The second reason is that we assumed that the carcass availability for a particular missile type was split equally between Naval Weapon Stations. There are many other possibilities for discrepancies. However these two seem to be the most important. Some of these other possibilities are described below.

The asset availability constraint (EQ. 6 of Chapter III) was used to assure that an NWS was not assigned more missiles to process than was available to them. The input data of LP1 and LP2 took carcass availability values for each type of missile from a CAIMS report. This particular CAIMS report did not provide these values by Naval Weapons Stations. For the purposes of this thesis it was assumed that half of the missile carcasses would be available at one NWS and the other half available to the other NWS.[4]

There is another CAIMS report which may be obtained that contains carcass availability data for each type of missile by Naval Weapons Station. Future use of LP1 and LP2 should rely on the data from this CAIMS report, by NWS, rather than assuming the carcass availability for a particular missile type is split equally between Weapons Stations.

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[4]No missile is maintained at more than 2 NWSs.

TABLE 5-2. COMPARISON OF MODEL AND ACTUAL DATA

Missile System	i	NWS	j	Missile Version	k	LP1 X_{ijk}	LP2 X_{ijk}	Actual X_{ijk}
SIDEWINDER	1	YT	1	AIM-9H	1	69	69	80
"	1	SB	2	"	1	298	298	24
"	1	YT	1	AIM-9L	2	50	50	96
"	1	SB	2	"	2	241	241	26
"	1	YT	1	AIM-9M	3	0	0	100
"	1	SB	2	"	3	0	0	86
"	1	YT	1	9M UPGRADE	4	291	291	56
"	1	SB	2	"	4	0	0	32
SPARROW	2	YT	1	AIM-7E	1	23	23	20
"	2	CC	3	"	1	17	17	6
"	2	YT	1	AIM-7F	2	0	0	110
"	2	CC	3	"	2	124	124	72
"	2	YT	1	BPD	3	16	16	39
"	2	CC	3	"	3	91	91	22
"	2	YT	1	IPD	4	40	40	32
"	2	CC	3	"	4	161	161	53
"	2	YT	1	AIM-7M	5	42	42	58
"	2	CC	3	"	5	0	0	5
"	2	YT	1	RIM-7M	6	0	0	14
"	2	CC	3	"	6	0	0	0
WALLEYE	3	YT	1	I	1	345	345	80
"	3	SB	2	"	1	98	98	46
"	3	YT	1	I ER/DL	2	47	47	10
"	3	SB	2	"	2	0	0	24
"	3	YT	1	DPSK	3	0	0	0
"	3	SB	2	"	3	0	0	28
"	3	YT	1	II ER/DL	4	6	6	19
"	3	SB	2	"	4	125	125	40
SHRIKE	4	YT	1	AGM-45	1	387	167	247
"	4	SB	2	"	1	0	0	150
PHOENIX	5	YT	1	AIM-54	1	42	42	190
"	5	SB	2	"	1	322	322	182
HARM	6	YT	1	AGM-88	1	33	33	0
"	6	SB	2	"	1	0	0	20
HARPOON	7	YT	1	(A)	1	0	0	19
"	7	CC	3	"	1	0	0	0
"	7	YT	1	(R)	2	0	0	37
"	7	CC	3	"	2	80	0	6
"	7	YT	1	(U)	3	0	0	9
"	7	CC	3	"	3	71	0	2

Since the cost to process the total mix of missiles given by LP2 is identical to the total actual historical cost of processing for the given time period, it is simpler to compare LP2 and the actual mix. The major difference is that LP2 recommends that no HARPOON missiles be processed, while the actual mix shows that many HARPOON missiles were processed. This is due to the fact that the processing cost for HARPOON is much greater than the other missile systems, and the model attempts to assign missiles of the cheaper versions to be processed first. If the user decides HARPOON´s are required, this can be accomplished by assigning a higher priority, K_{ik}, to HARPOON and running the model.

Table 5-3 shows how the model would have affected the asset readiness figures. Absolute values of asset readiness are avoided to preclude classification, therefore the change in asset readiness (ARO-AR) is tabulated. The missile asset readiness can be computed for each system assuming that the missile mix offered by LP1 and LP2 were followed. These values were then subtracted from the ARO for each system and tabulated in Table 5-3.

The data shows that if the workload plan recommended by LP1 was followed, all systems would have met their ARO´s with SPARROW RIM-7M exceeding its ARO by six percentage points.[5]

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[5]Sparrow RIM-7M was ahead of its ARO before starting.

TABLE 5-3. COMPARISON OF ASSET READINESS PREDICTED BY THE MODEL AND ACTUAL DATA

Missile System	i	Missile Version	k	ARO-ARa[1] Actual	ARO-AR2[2] LP2	ARO-AR1[3] LP1
SIDEWINDER	1	AIM-9H	1	18	0	0
"	1	AIM-9L	2	16	0	0
"	1	AIM-9M	3	-1	0	0
"	1	9M UPGRADE	4	-1	0	0
SPARROW	2	AIM-7E	1	39	0	0
"	2	AIM-7F	2	0	0	0
"	2	BPM	3	5	0	0
"	2	IPD	4	1	0	0
"	2	AIM-7M	5	-6	0	0
"	2	RIM-7M	6	-6	-6	-6
WALLEYE	3	I	1	-	0	0
"	3	I ER/DL	2	-	0	0
"	3	DPSK	3	-	0	0
"	3	I ER/DL	4	-	0	0
SHRIKE	4	AGM-45	1	6	5	0
PHOENIX	5	AIM-54	1	7	0	0
HARM	6	AGM-88	1	1	0	0
HARPOON	7	(A)	1	1	0	0
"	7	(R)	2	-3	11	0
"	7	(U)	3	8	11	0

1 - ARa is the actual asset readiness at the end of the quarter
2 - AR2 is the asset readiness if the mix of missiles recommended by LP2 would have been processed
3 - AR1 is the asset readiness if the mix of missiles recommended by LP1 would have been processed

If the output recommendations from LP2 had been followed, only SHRIKE and HARPOON would have been below their ARO´s. In comparing LP2 with the actual data for the time period it can be seen that many more systems could have met their ARO´s with the same budget.

The differences in asset readiness obtained in this table could be due to other factors, such as missile carcass non-availability, repair equipment failures, or a variety of circumstances. Whatever the reasons, Table 5-3 shows that LP2 can be a valuable planning guide when trying to maximize overall asset readiness.

VI. CONCLUSIONS AND RECOMMENDATIONS

The three linear programming models presented in this thesis would aid the Naval Air Systems Command and the missile workload planner in the management of processing air launched missiles through the Naval Weapons Stations. The models would not replace the workload planner, but would instead provide a quantitative basis for the planner to start with.

All three models would be useful depending upon the particular situation at hand. LP1 would be useful for the Naval Air Systems Command planner who could utilize the output to determine future budget requirements. Since LP1 determines the missile mix which minimizes the cost of meeting all ARO´s, this cost could be stated as the minimum budget required.

LP2 would be most useful to the workload planner who is working with budgetary constraints. If the available funding is less than the minimum cost provided by LP1, the user would be required to use LP2. The workload planner could use LP2 to maximize the overall effectiveness within this budget constraint. The model also gives the workload planner the flexibility to assign relative priorities to individual missile systems.

LP3 would be most useful to the Naval Air Systems Command in long range planning for maintenance and test facilities. For instance, the user could combine IPM data (up to 7 years in the future) and LP3 to determine the optimal mix of repair channels. Also, if LP1 gives an infeasible solution because insufficient repair channels exist to meet ARO´s, then the user would need LP3 to determine which additional repair channels are required.

While the data provided here shows that the model will work, the true feasibility and acceptability of the model will depend upon the accuracy of the input data and projections.

The following recommendations are provided to enhance the feasibility and to aid implementation of the model:

(1) The Naval Air Systems Command should buy the rights to a linear programming software package such as LINDO. The LINDO software used to solve the linear programs was adequate for LP1 and LP2. However, LP3 could be greatly enhanced by math programming software which also provides greater integer programming capacity.

(2) The Naval Air Systems Command should upgrade CAIMS to obtain data on In-Transit missiles, so that better estimates of U_{ijk}, T_{ijk}, and I_{ijk} can be made. A database should be created to allow better estimates of C_{ijk} and W_{ijk}.

(3) Currently, LP1, LP2, and LP3 don't assist the workload planner with decisions concerning certain aspects of the missile modification process. In this process, the workload planner may have to decide whether or not to remove RFI missiles from storage in order to do the modifications on them.[6] For example if a modification is required for a specific missile system, the workload planner will need to weigh such variables as the priority of the modification, the modification kit carrying cost, and the cost of modifying the RFI assets. An important future research effort would be to develop optimization tools which can assist the workload planner with missile modification planning.

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[6]Ordinarily, missile modifications are made to NRFI missiles in the course of their routine trips to intermediate or depot level maintenance. However, if more modification kits are available in a given quarter than NRFI missile carcasses, the workload planner must decide whether to install the remaining modification kits immediately (on RFI missiles from storage), or carry the kits over into the next quarter.

APPENDIX A

FORMULATION OF THE OBJECTIVE FUNCTION

In order to write the objective function for LP2 in the form required for linear programming, it was necessary to simplify equation 7 to the form shown in equation 9.

$$\text{EQ. (7)} \quad \text{MIN} \sum_{i=1}^{7} \sum_{k=1}^{M_i} K_{ik} \left(A_{ik} - R_{ik}\right)^2$$

Equation 7 is the basic equation to be minimized. Since

$$R_{ik} = 1 - \sum_{j=1}^{3} \frac{U_{ijk} + I_{ijk} - X_{ijk}}{T_{ik}}$$

which represents the actual missile asset readiness achieved. Equation 7 can be written as

$$\text{EQ. (8)} \quad \text{MIN} \sum_{i=1}^{7} \sum_{k=1}^{M_i} K_{ik} \left(A_{ik} - 1 + \sum_{j=1}^{3} \frac{U_{ijk}+I_{ijk}-X_{ijk}}{T_{ik}} \right)^2$$

The square of EQ. 8 still needs to be eliminated in order to write the objective function in the proper form. The square can be eliminated by adding the constraint given in equation 13.

$$\text{EQ. (13)} \quad \sum_{j=1}^{3} X_{ijk} \leq T_{ik}(A_{ik}-1)+ \sum_{j=1}^{3} (U_{ijk}+I_{ijk}) \quad \text{For all } i,k$$

If it were not for this constraint, the model would continue assigning more missiles to be processed thus minimizing the objective function. Equation 13 now requires that once each missile system and version has attained its ARO, then no more missiles will be assigned to that decision variable. Now that the square has been dropped from equation 8 it can be simplified as

$$\text{EQ. (8a)} \quad \text{MIN} \sum_{i=1}^{7} \sum_{k=1}^{M_i} K_{ik}A_{ik}-K_{ik} + K_{ik} \sum_{j=1}^{3} \frac{U_{ijk}+I_{ijk}-X_{ijk}}{T_{ik}}$$

Since K_{ik}, A_{ik}, U_{ijk}, and I_{ijk} are all constants for a given missile system and version, these terms can be dropped from equation 8a. Equation 9 results from dropping those terms. Minimizing this equation subject to the constraint of equation 13 is equivalent to minimizing the original equation 7.

$$\text{EQ. (9)} \quad \text{MIN} \sum_{i=1}^{7} \sum_{k=1}^{M_i} - K_{ik}/T_{ik} \sum_{j=1}^{3} X_{ijk}$$

APPENDIX B

NPS LINDO USER´S GUIDE

The formulations used in this thesis are set for the second quarter of FY 1986. Two methods could be used to run the models on a recurring basis. First, the user could become familiar with the linear programming formulations of LP1, LP2, and LP3 and change the input data file periodically using the formulas of Chapter III. Second, a simple computer program could be written to query the user for the input data and then solve the equations of Chapter III. At the Naval Postgraduate School a procedure was written in IBM CMS EXEC2 language for use on the IBM 3033AP CMS. This EXEC file is shown in Table B-1. The following steps are required to run LP1, LP2, and LP3 using this EXEC:

NOTE: In the following steps all commands and character strings to be typed in by the user will be written in capital letters. The symbol <fn> will be used to denote a user chosen file name.

(1) Log on to the mainframe computer which has the LINDO software and the data file.

(2) Type LP <fn> DATA where <fn> is the name of the file containing the formulation of the linear program in LINDO format.

(3) The LINDO program will prompt with a colon. A TAKE command allows the user to take the data file

temporarily during a terminal session. Type TAKE to do this. The LINDO program will query the user for a UNIT file. This file number is assigned by the CMS EXEC shown in Table B-1. Type 22 for this unit number.

(4) The LINDO program will then prompt with a colon. A DIVERT command allows the user to divert the output from the screen to a data listing file assigned by the CMS EXEC File. Type DIVERT to do this. The LINDO program will query the user for a unit file. This is a file number assigned by the CMS EXEC File. Type 21 for this unit number. The program will now assign the output to a listing file on the same disk as the data file.

(5) The LINDO program will now prompt with a colon. To run the model type " GO ".

(6) The LINDO program will now prompt with a colon. Type QUIT to leave LINDO.

(7) To examine the solution provided by LINDO the user may use ordinary CMS commands to print the data file created by the DIVERT command, or the user may look at the data file using any mainframe editor.

Another method to run LP1, LP2, and LP3 would be to write a computer program. This program would query the user for the input data elements such as C_{ijk}, U_{ijk}, I_{ijk}, etc. The program could then calculate all of the coefficients and right-hand side variables using the equations of Chapter III.

The program could then set up the problem formulation as shown in Appendix C and the user could use the steps above to run the model.

TABLE B-1. LP EXEC

```
 &TRACE OFF
*EXEC TO USE LINDO
 CLRSCRN
 &TYPE
 &TYPE LP SOLVER USING LINDO...
 &TYPE
 -READ
 &IF &N GT 0 &GOTO -FILES
 &TYPE LP PROBLEM NAME?
 &ARGS
 &GOTO -READ
 -FILES
 FILEDEF 05 TERM               (RECFM FB  LRECL   133 BLKSIZE   133
 FILEDEF 06 TERM               (RECFM FB  LRECL 32754 BLKSIZE 32754
 FILEDEF 20 DISK &1 BINARY  A4 (RECFM VBS LRECL 32754 BLKSIZE 32754
 FILEDEF 21 DISK &1 LISTING A1 (RECFM FBA LRECL   133 BLKSIZE   133
 FILEDEF 22 DISK &1 DATA    A1 (RECFM FB  LRECL    80 BLKSIZE    80
 &TYPE
 FILE
 &TYPE
 STATE &1 BINARY
 &TYPE FILE 20 IS FOR SAVE/RETR
 &IF &RC EQ 0 &TYPE FURTHER EXECUTION MAY ERASE FILE 20: &1 BINARY
 STATE &1 LISTING
 &TYPE FILE 21 IS FOR DIVERT OUTPUT
 &IF &RC EQ 0 &TYPE FURTHER EXECUTION MAY ERASE FILE 21: &1 LISTING
 STATE &1 DATA
 &TYPE 22 IS FOR DIVERT/TAKE
 &IF &RC EQ 0 &TYPE FURTHER ECECUTION MAY ERASE FILE 22: &1 DATA
 &TYPE
 &TYPE WANT TO CONTINUE (Y/N)?
 -ASK
 &READ VARS &YESNO
 &IF .YESNO NE .Y &IF .&YESNO NE .NO &GOTO -ASK
 &IF .&YESNO EQ .N &GOTO -EXITOUT
*USER SAYS O.K., NOW CHECK FOR LINDO
 STATE LINDO MODULE
 &IF &RC EQ 0 &GOTO -SOLVE
 &TYPE
 &TYPE LINDO NOT FOUND
 &TYPE WANT TO LINK TO LINDO NOW (AS 291 C-DISK) (Y/N)?
 -QUERY
 &READ VARS &YESNO
 &IF .&YESNO NE .Y &IF .&YESNO NE .N &GOTO -QUERY
 &F .&YESNO EQ .N &GOTO -EXITOUT
 CP LINK 1344P 191 291 RR PASS= GNET
 ACC 291 C
 -SOLVE
 LINDO
 -EXITOUT
```

APPENDIX C

LP1 FORMULATION

MIN $\{2031X_{111}+1688X_{121}+1624X_{112}+1314X_{122}+1502X_{113}+$
$1125X_{123}+377X_{114}+417X_{124}+3080X_{211}+4981X_{231}+$
$1659X_{212}+1477X_{232}+2077X_{213}+2023X_{233}+1732X_{214}+$
$1615X_{234}+1508X_{215}+1947X_{235}+3505X_{216}+5073X_{236}+$
$1219X_{311}+1270X_{321}+1515X_{312}+1749X_{322}+2834X_{313}+$
$1177X_{323}+1869X_{314}+1401X_{324}+878X_{411}+934X_{421}+$
$1521X_{511}+1240X_{521}+2094X_{611}+2393X_{621}+6920X_{711}+$
$4628X_{731}+7233X_{712}+6292X_{732}+11532X_{713}+11168X_{733}\}$

SUBJECT TO: $X_{111}+X_{121} > 367$

$X_{112}+X_{122} > 291$

$X_{113}+X_{123}+X_{114}+X_{124} > 291$

$X_{211}+X_{231} > 40$

$X_{212}+X_{232} > 124$

$X_{213}+X_{233} > 107$

$X_{214}+X_{234} > 201$

$X_{215}+X_{235} > 42$

$X_{216}+X_{236} > 0$

$X_{311}+X_{321} > 443$

$X_{312}+X_{322} > 47$

$X_{313}+X_{323} > 0$

$X_{314}+X_{324} > 131$

$X_{411}+X_{421} > 387$

$X_{511}+X_{521} > 364$

APPENDIX C

LP1 FORMULATION (CONTINUED)

$X_{611}+X_{621} > 33$

$X_{711}+X_{731} > 0$

$X_{712}+X_{732} > 80$

$X_{713}+X_{733} > 71$

$X_{111}+X_{112}+X_{113}+X_{114} < 4286$

$X_{121}+X_{122}+X_{123}+X_{124} < 6429$

$X_{211}+X_{212}+X_{213}+X_{214}+X_{215}+X_{216} < 3750$

$X_{231}+X_{232}+X_{233}+X_{234}+X_{235}+X_{236} < 4286$

$X_{321}+X_{322}+X_{323}+X_{324} < 2687$

$X_{421} < 4286$

$X_{511} < 2169$

$X_{521} < 2169$

$X_{621} < 1622$

$X_{731}+X_{732}+X_{733} < 1078$

$.056X_{311}+.056X_{312}+.056X_{313}+.056X_{314}+$

$.167X_{711}+.167X_{712}+.167X_{713} < 180$

$.048X_{411}+.167X_{611} < 180$

$X_{111} < 298$

$X_{121} < 298$

$X_{112} < 241$

$X_{122} < 241$

$X_{113}+X_{114} < 398$

$X_{123}+X_{124} < 398$

$X_{211} < 23$

APPENDIX C

LP1 FORMULATION (CONTINUED)

$X_{231} < 23$

$X_{212} < 160$

$X_{232} < 160$

$X_{213} < 91$

$X_{233} < 91$

$X_{214} < 161$

$X_{234} < 161$

$X_{215} < 100$

$X_{235} < 100$

$X_{216} < 13$

$X_{236} < 13$

$X_{311} < 345$

$X_{321} < 345$

$X_{312} < 50$

$X_{322} < 50$

$X_{313} < 26$

$X_{323} < 26$

$X_{314} < 125$

$X_{324} < 125$

$X_{411} < 510$

$X_{421} < 510$

$X_{511} < 322$

$X_{521} < 322$

APPENDIX C

LP1 FORMULATION (CONTINUED)

$X_{611} < 47$

$X_{621} < 47$

$X_{711} < 42$

$X_{731} < 42$

$X_{712} < 92$

$X_{732} < 92$

$X_{713} < 82$

$X_{733} < 82$

END

APPENDIX D

LP2 FORMULATION

$$MAX \{.062x_{111}+.062X_{121}+.073X_{112}+.073X_{122}+.028X_{113}+$$

$$.028X_{123}+.028X_{114}+.028X_{124}+3.85X_{211}+.3.85X_{231}+$$

$$.072X_{212}+.072X_{232}+.214X_{213}+.214X_{233}+.127X_{214}+$$

$$.127X_{234}+.089X_{215}+.089X_{235}+.213X_{216}+.213X_{236}+$$

$$.057X_{311}+.057X_{321}+.269X_{312}+.269X_{322}+.129X_{313}+$$

$$.129X_{323}+.118X_{314}+.118X_{324}+.022X_{411}+.022X_{421}+$$

$$.050X_{511}+.050X_{521}+.231X_{611}+.231X_{621}+.160X_{711}+$$

$$.160X_{731}+.136X_{712}+.136X_{732}+.151X_{713}+.151X_{733}\}$$

SUBJECT TO:

$$2031X_{111}+1688X_{121}+1624X_{112}+1314X_{122}+1502X_{113}+$$

$$1125X_{123}+377X_{114}+417X_{124}+3080X_{211}+4981X_{231}+$$

$$1659X_{212}+1477X_{232}+2077X_{213}+2023X_{233}+1732X_{214}+$$

$$1615X_{234}+1508X_{215}+1947X_{235}+3505X_{216}+5073X_{236}+$$

$$1219X_{311}+1270X_{321}+1515X_{312}+1749X_{322}+2834X_{313}+$$

$$1177X_{323}+1869X_{314}+1401X_{324}+878X_{411}+934X_{421}+$$

$$1521X_{511}+1240X_{521}+2094X_{611}+2393X_{621}+6920X_{711}+$$

$$4628X_{731}+7233X_{712}+6292X_{732}+11532X_{713}+11168X_{733} < 3,580,701$$

$$X_{111}+X_{112}+X_{113}+X_{114} < 4286$$

$$X_{121}+X_{122}+X_{123}+X_{124} < 6429$$

$$X_{211}+X_{212}+X_{213}+X_{214}+X_{215}+X_{216} < 3750$$

$$X_{231}+X_{232}+X_{233}+X_{234}+X_{235}+X_{236} < 4286$$

$$X_{321}+X_{322}+X_{323}+X_{324} < 2687$$

$$X_{421} < 4286$$

$X_{511} < 2169$

$X_{521} < 2169$

$X_{621} < 1622$

$X_{731}+X_{732}+X_{733} < 1078$

$.056X_{311}+.056X_{312}+.056X_{313}+.056X_{314}+.167X_{711}+$

$.167X_{712}+.167X_{713} < 180$

$.048X_{411}+.167X_{611} < 180$

$X_{111}+X_{121} < 367$

$X_{112}+X_{122} < 291$

$X_{113}+X_{123}+X_{114}+X_{124} < 291$

$X_{211}+X_{231} < 40$

$X_{212}+X_{232} < 124$

$X_{213}+X_{233} < 107$

$X_{214}+X_{234} < 201$

$X_{215}+X_{235} < 42$

$X_{216}+X_{236} < 0$

$X_{311}+X_{321} < 443$

$X_{312}+X_{322} < 47$

$X_{313}+X_{323} < 0$

$X_{314}+X_{324} < 131$

$X_{411}+X_{421} < 387$

$X_{511}+X_{521} < 364$

$X_{611}+X_{621} < 33$

$X_{711}+X_{731} < 0$

LP2 FORMULATION (CONTINUED)

$X_{712}+X_{732} < 80$

$X_{713}+X_{733} < 71$

$X_{111} < 298$

$X_{112} < 298$

$X_{112} < 241$

$X_{122} < 241$

$X_{113}+X_{114} < 398$

$X_{123}+X_{124} < 398$

$X_{211} < 23$

$X_{231} < 23$

$X_{212} < 160$

$X_{232} < 160$

$X_{213} < 91$

$X_{233} < 91$

$X_{214} < 161$

$X_{234} < 161$

$X_{215} < 100$

$X_{235} < 100$

$X_{216} < 13$

$X_{236} < 13$

$X_{311} < 345$

$X_{321} < 345$

$X_{312} < 50$

$X_{322} < 50$

APPENDIX D

LP2 FORMULATION (CONTINUED)

$X_{313} < 26$

$X_{323} < 26$

$X_{314} < 125$

$X_{324} < 125$

$X_{411} < 510$

$X_{421} < 510$

$X_{511} < 322$

$X_{521} < 322$

$X_{611} < 47$

$X_{621} < 47$

$X_{711} < 42$

$X_{731} < 42$

$X_{712} < 92$

$X_{732} < 92$

$X_{713} < 82$

$X_{733} < 82$

END

APPENDIX E

LP3 FORMULATION

$$\text{MIN } \{2031X_{111}+1688X_{121}+1624X_{112}+1314X_{122}+1502X_{113}+$$
$$125X_{123}+377X_{114}+417X_{124}+3080X_{211}+4981X_{231}+1659X_{212}$$
$$177X_{232}+2077X_{213}+2023X_{233}+1732X_{214}+1615X_{234}+1508X_{214}+$$
$$1947X_{235}+3505X_{216}+5073X_{236}+1219X_{311}+1270X_{321}+$$
$$1515X_{312}+1749X_{322}+2834X_{313}+1177X_{323}+1869X_{314}+$$
$$401X_{324}+878X_{411}+934X_{421}+1521X_{511}+1240X_{521}+2094X_{611}$$
$$12393X_{621}+6920X_{711}+4628X_{731}+7233X_{712}+6292X_{732}+$$
$$1500Y_{31}+500Y_{32}+50Y_{41}+50Y_{42}+3000Y_{51}+3000Y_{52}+$$
$$2000Y_{61}+2000Y_{62}+3000Y_{71}+3000Y_{73}\}$$

SUBJECT TO: $X_{111}+X_{121} > 734$

$X_{112}+X_{122} > 582$

$X_{113}+X_{123}+X_{114}+X_{124} > 582$

$X_{211}+X_{231} > 80$

$X_{212}+X_{232} > 248$

$X_{213}+X_{233} > 214$

$X_{214}+X_{234} > 402$

$X_{215}+X_{235} > 84$

$X_{216}+X_{236} > 100$

$X_{311}+X_{321} > 886$

$X_{312}+X_{322} > 94$

$X_{313}+X_{323} > 100$

$X_{314}+X_{324} > 262$

$X_{411}+X_{421} > 774$

APPENDIX E

LP3 FORMULATION (Continued)

$X_{511}+X_{521} > 728$

$X_{611}+X_{621} > 66$

$X_{711}+X_{731} > 100$

$X_{712}+X_{732} > 160$

$X_{713}+X_{733} > 142$

$X_{111}+X_{112}+X_{113}+X_{114}-715Y_{11} < 715$

$X_{121}+X_{122}+X_{123}+X_{124}-1071Y_{12} < 1071$

$X_{211}+X_{212}+X_{213}+X_{214}+X_{215}+X_{216}-625Y_{21} < 625$

$X_{231}+X_{232}+X_{233}+X_{234}+X_{235}+X_{236}-715Y_{23} < 715$

$X_{321}+X_{322}+X_{323}+X_{324}-448Y_{32} < 448$

$X_{421}-715Y_{42} < 7159$

$X_{511}-362Y_{51} < 362$

$X_{512}-362Y_{52} < 362$

$X_{621}-271Y_{62} < 271$

$X_{731}+X_{732}+X_{733}-180Y_{73} < 180$

$.056X_{311}+.056X_{312}+.056X_{313}+.056X_{314}+.167X_{711}+$

$.167X_{712}+.167X_{713}-30Y_{71}-30Y_{73} < 30$

$.048X_{411}+.167X_{611}-30Y_{61}-30Y_{41} < 30$

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