NAVAL POSTGRADUATE SCHOOL
MONTEREY, CALIFORNIA

THESIS

GENERALIZED OPTIMIZATION MODELING FOR DEFENSE CAPITAL PLANNING AND EQUIPMENT REPLACEMENT

by

Gregorio Ameyugo

September, 1996

Thesis Advisor: Gordon H. Bradley

Approved for public release; distribution is unlimited

REPORT DOCUMENTATION PAGE			Form Approved OMB No.0704
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.			
1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE September, 1996	3. REPORT TYPE AND DATES COVERED Master's Thesis	
4. TITLE AND SUBTITLE GENERALIZED OPTIMIZATION MODELING FOR DEFENSE CAPITAL PLANNING AND EQUIPMENT REPLACEMENT			5. FUNDING NUMBERS
6. AUTHOR(S) Gregorio Ameyugo			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSORING / MONITORING AGENCY REPORT NUMBER
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited			12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Recurring issues for Navy and DoD analysts are decisions on the upgrade, purchase, and retirement of equipment with high capital cost and long useful life. Since the PHOENIX model was developed in the late eighties a number of theses addressing different equipment procurement and modernization problems have been written at the Naval Postgraduate School. Those models have a common thread of purpose, data, and methods that suggest the possibility of building a common model subsuming those previous efforts.

The model developed is a mixed-integer linear program written in GAMS, and its most appealing characteristic is the spreadsheet application that allows the user to enter data, solve the model, analyze its output, enter user feedback in the process of finding a new solution, and also to manage a collection of candidate solutions.

With this approach difficulties are hidden from the user who interacts only with the spreadsheet and does not have to build his own model. The combination of a generic model and the visual programming capability of the spreadsheet provides the user with a tool to accomplish more complete, complex and sophisticated analysis.

14. SUBJECT TERMS Military- Cost Effectiveness Programming- Integer Applications- Finance - Capital Budgeting.			15. NUMBER OF PAGES 77
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

GENERALIZED OPTIMIZATION MODELING FOR DEFENSE CAPITAL PLANNING AND EQUIPMENT REPLACEMENT

Gregorio Ameyugo
Lieutenant Commander, Spanish Navy

Submitted in partial fulfillment of the
requirements for the degree

MASTER OF SCIENCE IN OPERATIONS RESEARCH

from the

NAVAL POSTGRADUATE SCHOOL

September 1996

Author: ______________________
Gregorio Ameyugo

Approved by: ______________________
Gordon H. Bradley, Thesis Advisor

____
Gerald G. Brown, Second Reader

____
Frank Petho, Chairman
Department of Operations Research

ABSTRACT

Recurring issues for Navy and DoD analysts are decisions on the upgrade, purchase, and retirement of equipment with high capital cost and long useful life. Since the PHOENIX model was developed in the late eighties a number of theses addressing different equipment procurement and modernization problems have been written at the Naval Postgraduate School. Those models have a common thread of purpose, data, and methods that suggest the possibility of building a common model subsuming those previous efforts.

The model developed is a mixed-integer linear program written in GAMS, and its most appealing characteristic is the spreadsheet application that allows the user to enter data, solve the model, analyze its output, enter user feedback in the process of finding a new solution, and also to manage a collection of candidate solutions.

With this approach difficulties are hidden from the user who interacts only with the spreadsheet and does not have to build his own model. The combination of a generic model and the visual programming capability of the spreadsheet provides the user with a tool to accomplish more complete, complex and sophisticated analysis.

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.

TABLE OF CONTENTS

EXECUTIVE SUMMARY

With declining budgets, capital planning for equipment replacement has become an even more important part of defense planning. Recurring issues for Navy and DoD analysts are decisions on the upgrade, purchase, and retirement of equipment with high capital cost and long useful life. Typical analyses involve specific types of ships, planes, helicopters, tanks, wheeled vehicles, etc., whose useful life is 10, 20, or more years. Purchase and upgrade options involve determining production quantities and scheduling production facilities that have capacity limitations and significant fixed and variable costs. For each year in the planning horizon and each of the missions considered, the mix of combat-ready equipment must satisfy requirements on the number, age, fraction with certain critical requirements, and other limitations that reflect projected combat requirements. There is a budget constraint each year on funds to expend on operations and maintenance and on upgrade and purchase.

These capital planning and equipment replacement problems are difficult to analyze because the data on requirements and costs are hard to determine and validate, especially for 10, 20, or 30 years into the future. Also, these models contain a variety of economic assumptions that must be carefully considered. In addition, typical studies involve computing decisions for a large number of possible scenarios and different assumptions. Finally, these results must be presented in an unbiased form that allows comparison and analysis.

Linear programming is very well suited to civilian capital planning where profit is measured in the same units as expenses and the objective function is clearly defined by the maximization of owners' wealth. These conditions do not apply automatically to defense problems. The reason is that there is no way to measure in dollars the ultimate worth of defense, and we do not have a single measure of effectiveness for different choices because what is required is to maximize the public's welfare. As a consequence, national security decisions are conditioned by military judgment. Nevertheless, decision makers can still benefit from an optimization approach.

This thesis develops a model and a spreadsheet based computer system that allows force planners to evaluate the effect and cost of different force modernization policies over an extended planning horizon. The aim of this model is to facilitate the formulation, iterative solution, and analysis of a modernization problem. This approach provides the decision maker with many proposals for consideration. The side-by-side comparison of proposals allows a better grasp of the project's coherence and a greater degree of uniformity in judging them. This systematic approach melds into a single tool a combination of automatic calculation and human judgment for the solution of the procurement and modernization problem. An additional advantage of this approach is that the analyst doesn't need to be an expert programmer with the skills or the time to build his own model.

The problem is modeled as a mixed-integer linear program written in the General Algebraic Modeling System (GAMS). There is a discussion of the economic considerations for all Government Capital Planning Studies. These include the treatment of inflation and the capital cost, and how to incorporate them into the model.

This model and its spreadsheet interface respond to the need for a user interface and a graphical analysis tool for equipment replacement problems. The model solves, under the proper assumptions, the Equipment Replacement Problem providing the following features:

- Use of elastic constraints to prevent unfeasible solutions;
- Interactive change of the penalty weights to allow the input of user judgment in the construction of a satisfactory solution; and
- Graphic output representation and storing of different solutions to facilitate their assessment and comparison.

Computing details are hidden from the user who interacts only with the spreadsheet. The combination of a generic model and the visual programming capability of the spreadsheet provides the user with a tool to execute more complete, complex and sophisticated analysis.

The operations research approach uncovers the relationship between the economic dimension of the problem and meaningful indicators of military performance. The military executive can get a clear picture of what has to be sacrificed in one area in order to gain something in another. Gains and losses are not measured in common units but in those indicators that makes sense for the military expert making the decisions. The process of side-by-side comparisons obviously facilitates a final judgment. Decision makers have access to a large amount of impartial information about the trade-offs involved in their conflicting objectives. The final decision remains a matter of judgment, but the basis to judge has been improved, and with that the quality of the decision.

I. INTRODUCTION

A. PROBLEM DESCRIPTION

With declining budgets, capital planning for equipment replacement has become an even more important part of defense planning. Recurring issues for Navy and DoD analysts are decisions on the upgrade, purchase, and retirement of equipment with high capital cost and long useful life. Typical analyses involve specific types of ships, planes, helicopters, tanks, wheeled vehicles, etc., whose useful life is 10, 20, or more years. Purchase and upgrade options involve determining production quantities and scheduling production facilities that have capacity limitations and significant fixed and variable costs. For each year in the planning horizon and each of the missions considered, the mix of combat-ready equipment must satisfy requirements on the number, age, fraction with certain critical requirements, and other limitations that reflect projected combat requirements. There is a budget constraint each year on funds to expend on operations and maintenance and on upgrade and purchase.

These capital planning and equipment replacement problems are difficult to analyze because the data on requirements and costs are hard to determine and validate, especially for 10, 20, or 30 years into the future. Also, these models contain a variety of economic assumptions that must be carefully considered. In addition, typical studies involve computing decisions for a large number of possible scenarios and different assumptions. Finally, these results must be presented in an unbiased form that allows comparison and analysis.

B. OPERATIONS RESEARCH APPROACH

Modernization decisions require choices between alternate courses of action, and the choice of a particular alternative will have far-reaching consequences because it ties up capital in a specific way and because the decision determines future military capabilities. Operations research is concerned with rational choices among alternatives; military capital investment problems are one of the areas of its application. Since the early 1960's linear programming has been applied to civilian capital budgeting decisions; this technique was applied to military capital decisions some years later.

C. AUTOMATIC SOLUTION VERSUS DECISION MAKER JUDGMENT

Charles Hitch, former Assistant Secretary of Defense wrote, "Now the last thing I want to do is to leave the impression that we believe that optimal strategies can be calculated on slide rules or even high-speed computers. Nothing can be further from the truth." (Hitch, 1963) His statement remains true today.

Linear programming is very well suited to civilian capital planning where profit is measured in the same units as expenses and the objective function is clearly defined by the maximization of owners wealth. These conditions do not apply automatically to defense problems. The reason is that there is no way to measure in dollars the ultimate worth of defense, and we do not have a single measure of effectiveness for different choices because what is required is to maximize the public's welfare. As a consequence, national security decisions are conditioned by military judgment. Nevertheless, decision makers can still benefit from an optimization approach.

This thesis develops a model and its graphical interface that, as a decision aid, allows force planners to evaluate the effect and cost of different force modernization policies over an extended planning horizon. The aim of this model is to facilitate the formulation, iterative solution, and analysis of a modernization problem. This approach provides the decision maker with many proposals for consideration. The side-by-side comparison of proposals allows a better grasp of the project's coherence and a greater degree of uniformity in comparing them. This systematic approach melds into a single tool a combination of automatic calculation and human judgment for the solution of the procurement and modernization problem. An additional advantage of this approach is that the analyst doesn't need to be an expert programmer with the skills or the time to build his own model.

However, the output of analytical models is information, not decisions, and so the role of experience and judgment remains and, furthermore, its relevance is enhanced by the use of this tool.

II. PREVIOUS LITERATURE

A. PREVIOUS MODELS

Solving capital budgeting problems with linear programming was first suggested in 1963, (Weingartner 1963), but it was not until about 25 years later that this was incorporated into large-scale military expenditure planning. Naval Postgraduate School (NPS) faculty and graduates played an important role in introducing this approach. One key project was prompted by the realization by the US Army in 1988 that it did not have a comprehensive plan for modernizing its helicopter fleet which was composed of Vietnam-era aircraft nearing the end of their useful lives. The Army Force System Directorate commissioned the "Army Aviation Modernization Trade-Off Requirement Study (AAMTOR)" to address this problem. This study group was composed of NPS graduates at the US Army Concepts Analysis Agency and NPS faculty. They created the PHOENIX model.

PHOENIX (Brown et al. 1991) is a decision support system that optimizes procurement and modernization decisions over a 10 to 30 year planning horizon. The model is a variant of a classic operation research problem: the equipment replacement model. PHOENIX is a very large mixed-integer linear program implemented in a matrix generation program written in FORTRAN. It recognizes yearly operating, maintenance, retirement, service-life extension, and new procurement costs, subject to constraints on fleet age, technological mix, composition of the fleet, and budgets, over a multi-year planning horizon. The success of this model encouraged its application to the modernization of the army's fleet of tactical wheeled vehicles.

Another model used in modernization planning is FOMOA (Coblentz 1991). It is a scaled-down version of PHOENIX developed at the Army Concepts Analysis Agency that requires less data input and is more user-friendly but also is less sophisticated. For instance, it does not allow constraint violations, and the user must specify the opening and closing years of the production lines, rather than expect these to be optimally chosen.

B. OTHER RELATED THESES

After PHOENIX was developed in 1988, more optimization models applied to modernization projects were developed as theses at the Naval Postgraduate School. These were built at first in FORTRAN, then in FORTRAN and in the General Algebraic Modeling System (GAMS) (Brooke et al. 1992), and finally, in 1996, just in GAMS.

- "An Integer Programming Approach to Long Range Shipbuilding Scheduling," Faircloth, Joseph A. 1989. Advisor Richard Rosental.
  This is an optimization model for long-range shipbuilding scheduling; it is a FORTRAN and GAMS model that minimizes the penalties of not meeting requirements. It is not a sophisticated model; for instance, it does not consider average ship age. The thesis recommends the addition of a user-friendly front end and the addition of a graphic display of solutions.
- "An Integer Programming Model for Navy's Maritime Patrol Aviation Fleet," Drash , Robert W. 1990. Advisor Kevin Wood.
  This is an optimization model for maritime patrol aviation modernization. This model, written in FORTRAN, is a scaled down translation of the PHOENIX model that addresses a single mission problem and uses heuristics to shorten the solution time. It does not allow planning horizons longer than 10 years. It includes average age and technological constraints and minimizes cost and constraint violation penalties. Decisions are made for cohorts rather than for single aircraft. (All aircraft of the same type produced in the same year form a 'cohort').
- "Modeling Strategy for Large-Scale Optimization Based on Analysis and Visualization Principles," Bither, Cheryl A. and Dougherty, Julie A. 1991. Advisor Gordon H. Bradley.
  This thesis studies the presentation of PHOENIX results based on analysis and visualization principles. It analyzes and appraises the use of a graphic interface to study the PHOENIX model output.

- "An Optimization Model for Maritime Patrol Aviation Modernization Planning," Osborne, Brian A. 1993. Advisor Kevin Wood.
  This thesis is a follow-up of the Drash thesis cited above; the model is developed in GAMS and FORTRAN and again uses heuristics. The modernization decisions are for individual aircraft rather than cohorts. The years for opening and closing of production lines is directly input by the user. The author recommends the development of a user-friendly interface.
- "Optimizing Replacement of the U.S. Navy's CH-46D 'Sea Knight' Helicopter," Dundas, Joseph 1996. Advisor Siriphong Lawphongpanich.
  This thesis studies replacement alternatives for the CH-46D helicopter. The model is a scaled-down version of PHOENIX with some modifications. It considers only one type of aircraft, and the main difference with the PHOENIX model is that the author treats individual aircraft by their cumulative flight hours. This thesis is developed completely in GAMS and introduces a leasing option as a possible source of assets.

III. MODEL FORMULATION

A. DEFINITION AND GOAL

The common thread of purpose, data, and methods observed among the models and theses developed so far suggests that a unified view of modeling and analysis for defense capital planning and equipment replacement has the potential to reduce the effort and time for studies and simultaneously boost the quality of the analysis and the credibility of the results. The development of user-friendly tools and techniques, as recommended in those previous efforts, will reduce the time and effort required for future studies.

The problem is modeled as a mixed-integer linear program written in the General Algebraic Modeling System (GAMS). The mathematical formulation of the problem is shown in Appendix A. The GAMS code listing is available from the thesis advisor (bradley@nps.navy.mil).

B. ASSUMPTIONS

- The time unit is a year.
- The set of years over which the decisions span is called the 'planning horizon.'
- Each single unit to be replaced (ship, aircraft, helicopter, tank...) is called an 'asset.'
- All assets of the same type produced in the same year are called a 'cohort.'
- 'Mission' is a characteristic or capability that defines a subset in the assets under consideration.(i.e. cargo helicopter, attack submarine,...)
- Assets are paid for in a given year but are not delivered for use until after a fixed lag time. Modernization also has a lag time for each asset type.
- All expenditures are planned in constant dollars, using the first planning year as the base.
- Budgets and costs are discounted at a rate that will be provided by the user.
- Monies not committed a given year are not carried forward to subsequent years.

- A production line can either be producing a given type of asset or modernizing it, but both activities can not be concurrent on the same line during the same year.
- A production line can be opened only once in the planning horizon.
- Fixed costs incurred by opening and maintaining a production line are included in the model.
- Production lines have a minimum and maximum sustained annual rate of production.
- Production lines, if used, have a minimum and maximum cumulative number of units produced.
- A modernized asset is endowed with the same life limit as a new asset.

C. VARIABLES

INTEGER VARIABLES

- Number of assets of a given type that are to be built, by year, by production line.
- Number of assets of a given type that are to be modernized, by year, by production line.
- Number of assets of a given type and cohort that are to be retired, by year.
- Number of assets of a given type and cohort that are to be modernized, by year.
- Number of assets of a given type that, once modernized, join the fleet, by year.

BINARY VARIABLES

- Indicate when a production line is opened, and whether it is open for building new assets or to modernize.
- Two sets of variables that respectively indicate if a line remains open in successive years and the type of asset that is either being built or modernized there.

D. CONSTRAINTS

INVENTORY BALANCE CONSTRAINTS

Adjacent planning years should balance the number of their assets. This constraint keeps account of each individual asset. During a year each asset can either be modernized or retired or can remain operational. The inflow for each year is the previous year's ending inventory plus the newly constructed or modernized assets, and the outflow is the sum of the assets in the three basic states: modernized, retired, or operational. In the outflow the quantity of assets that remains in operational status is affected by an attrition rate. Different attrition rates for each asset type can be used, but it makes sense to use a value different from 1.0 only when asset numbers are large enough.

REQUIRED INVENTORY CONSTRAINTS

Each mission has its own operational requirements and a minimum number of assets required to accomplish them. The required inventory constraint ensures that sufficient assets are available in each planning year to satisfy mission requirements. This constraint is elastic, meaning that if the solution does not fall between a minimum and maximum desired inventory level, a linear penalty per unit violated will appear in the objective function.

HIGH TECHNOLOGY CONSIDERATION

In each planning year an asset is designated to contain, or not contain, high technology. For each year in the planning horizon, each mission has a required minimum fraction of assets with high technology. An asset can be downgraded from high technology after a given time. This constraint is also elastic.

AVERAGE AGE

The average age of each mission fleet should not exceed a policy-specified maximum, by year. This constraint is also elastic. In past studies the average age constraints have had a significant impact on the solution.

BUDGET

Costs should not exceed the budget range. Usually budgetary authority divides expenses into two primary categories that have their own budgets: "Procurement and Upgrade" expenses and "Operating and Maintenance Cost " (O&M) expenses. The budget constraints are imposed on the combined costs, however, the two expense categories are reported separately in the output.

PRODUCTION LINE CONSTRAINTS

The opening and closing years of a production line determine the production campaign for that particular line. There are two sets of constraints dealing with production lines: one for new construction and another for modernization.

One consideration involving production lines is the minimum and maximum purchase obligation. Many purchasing agreements specify a minimum and a maximum total number of assets. There are minimum and maximum total production campaign elastic constraints on units of assets in our model.

Also, each line has a maximum and minimum annual production capacity. Both limits are elastic in our model. The minimum bound will reflect the number of assets whose production will effectively employ the workforce. If the upper limit cannot be exceeded due to unavoidable physical limitations, we may set its penalty to very high value.

Another constraint prevents production gaps during a production campaign, and a final constraint will allow a line to open for the construction of new assets or for the modernization of them, but not for both.

Constraints such as these are the distinguishing essence of military capital equipment planning.

E. OBJECTIVE FUNCTION

In normal optimization problems alternate decisions are compared and evaluated by their outcome in the objective function; the choice of one suitable function is then of extreme importance. But in our problem we cannot reflect all our needs in a single decision criteria; in fact we have many partial criteria to consider and as a consequence we don't have a way of selecting the 'best' alternative automatically.

We selected one decision criteria that, even though not reflecting all our needs, will help the user compare alternatives: We minimize the sum of the total costs of owning and operating the fleet of assets plus the subjective penalties of not meeting the set of conflicting requirements. This decision criterion is included in the model through the penalty weights associated with each of our elastic constraints along the whole planning horizon.

A comparison of efficient alternatives shows the 'trade-offs' among conflicting objectives. The final choice, a matter of judgment by the decision maker, includes the reconciliation of those conflicting objectives.

IV. GRAPHICAL USER INTERFACE

A. DESCRIPTION

A well-chosen graph is an extremely powerful end-analysis tool. Our eye-brain system is the most sophisticated information processor ever developed, and through graphical displays we can put this eye-brain system to good use to get a quick and deep insight into our solution and its value for meeting our requirements.

The interface allows the user to input data, launch the optimization program, retrieve a graphical presentation of results, and manage different candidate solutions. The use of this tool speeds problem development, and the analysis tools provided by the spreadsheet application facilitates the process of developing a satisfactory solution.

Because of the magnitude of these budget decisions it is important to explore a large variety of alternate solutions resulting from differences in requirements, policy, and resources. To facilitate this task, inputs to the interface are linked to the optimizer and the resulting optimizer output is linked to the interface graphics. The user will interact with the interface in the following sequence: First the user will be prompted to enter requirements, policy, and resources as described below. Once all relevant data is introduced, the optimization program will be launched. The user will not deal directly with the optimization program. When the optimization program terminates, the user will be able to view the solution in the same interface. Using the graphics charts, the user sees not only the objective function but also which constraints are violated and to what extent. He is able to input feedback to the model by changing any of the penalty weights directly from the graphical screen and then repeat the process until he constructs a satisfactory solution.

B. WALK-THROUGH OF AN EXAMPLE ANALYSIS

In Appendix B the use of the system to analyze an example problem is demonstrated with a sequence of screen shots of the graphical user interface. The example shows the modernization of two asset types over a planning horizon of ten years using three production lines. The captions describe how a user enters data, launches the optimization and analyzes the solution. The iterative process of solution analysis, feedback to the model and reoptimization is also described.

C. EXCEL VISUAL BASIC APPRAISAL

The Graphic User spreadsheet application is developed in Excel (Microsoft Excel 1994).

ADVANTAGES OF A SPREADSHEET APPLICATION

- A spreadsheet allows the use of friendly dialog boxes with controls such as buttons and scroll bars.
- The spreadsheet eases data entry.
- It contains custom menus offering the user multiple choices.
- It produces high-quality graphs and charts.

ADVANTAGES OF EXCEL

- Excel uses a macro language which is a powerful object-oriented version of Visual Basic.
- Excel is an international standard, familiar to millions of users.
- Excel provides compatibility with other Microsoft applications which facilitates the transfer of data.
- The application can be compiled which protects it from uninformed tampering.
- It is a well developed, stable product.
- It has a relatively low cost.
- There is a wide selection of good books on graphic user interfaces (GUI) development (e.g., Walkenbach 1994).

D. FEEDBACK AND VALIDATION

We are not dealing with a single measure of effectiveness. Rather, we have to consider multiple and usually conflicting requirements. A higher degree of attainment in one objective usually lowers the levels of attainment in others. The best alternative cannot be defined in a deterministic way, and the final choice remains a matter of judgment.

The graphical output interface is part of the optimization process; it allows the user to analyze the results, input their direct feedback to the model by changing the weight of being outside the desired region for each of the constraints, and relaunch the optimization program. The complete process is both intuitive and iterative and should, eventually, end with a satisfactory solution.

A sensitivity analysis (determining the effect on the solution of small changes in the input) may identify areas for which accurate information is critical. For instance, if the user discovers the solution is very sensitive to the value of an estimated parameter, he may postpone a decision until more accurate information is available on that estimated value.

VALIDATION

Graphs can reveal information in a consistent way. This facilitates interpretation. They show relations between variables and how changes in one affects the others. Also, seeing the actual values produced by the solution simultaneously with the requirements helps the user to detect errors in the data input.

In general, it is obvious from the nature of the input and output data what trends the results should exhibit, and any deviation from the expected trends should be investigated. This graphic check is more effective and faster than the inspection of data files containing columns of numbers. When graphically displayed, time series become much more informative.

SINGLE RUN

We run the model with all inputs set at their best-known values. The user begins the analysis of the output by inspecting the objective function values and studying the graph with the cost values and the penalty values along the whole planning horizon. From there the user may jump to check each of the requirements and see how the solution for that particular constraint falls with respect to the required limits. Finally, the user can save this model and its solution under any chosen name.

The system constructs a solution to meet given requirements along a planning horizon. It obtains an optimum solution to the deterministic problem of meeting as closely as possible all our policy requirements while incurring a total minimum cost plus penalties during the whole planning horizon.

MULTIPLE RUNS

The user needs to consider many contingencies and to perform sensitivity analysis, so he may need to run variations. Two options are open here: he may proceed by modifying the actual solution or by producing a copy of the actual solution to be modified. The advantage of this latter option is that when a satisfactory solution is reached a complete history of intermediate solutions is available; the disadvantage is that each intermediate solution requires storage space on the disk. The spreadsheet application allows the user to manage those intermediate solutions, search and show any previous solution, and print them. This facilitates the comparison of candidate solutions.

In most cases we are going to accept a final solution with violations in one or more of our original requirements; which ones to violate and to what extent will be dictated by the judgment of the user. The selection of the final solution is greatly facilitated by using the graphic interface to compare alternatives.

V. MODEL USE CONSIDERATIONS

A. USER OF THE MODEL

The user of this model is intended to be the analyst and decision maker team. For the user the first task is to decide the alternatives he is willing to consider and the planning horizon that the study will cover. The solution cannot be better than the best alternative considered; so if we only consider poor alternatives the optimal solution will also be poor.

The analyst collects or produces the input data. Very often this is the most difficult part of the process since part of this input may not exist yet and developing the data may itself be an arduous task. The economic data in the model deserves careful consideration; all monies appearing within the planning horizon must be reduced to a common year. The next stage, model building, is solved by this thesis. The analyst doesn't need to write hundred of lines of code to build his own model. The final task, for which our system is again helpful, consists of repeatedly solving the model and studying and analyzing different solutions until a final decision can be reached; this job is again analyst and decision maker teamwork.

The hardware requirements to use the model presented in this thesis is a Personal Computer work station with operating system Windows 3.1 or better, Microsoft Excel Spreadsheet (Microsoft 1994), and the General Algebraic Modeling System program (Brooke et al. 1993).

B. PREPARING DATA INPUT TO THE MODEL

The development and input of sufficient alternatives requires a deep knowledge of the problem. The analyst has to prepare the data input starting with the main problem requirements (planning horizon and missions to cover), and the requirements for those missions (desired maximum and minimum average age of assets covering a particular mission, their desired technological split, and the maximum and minimum life we want for those assets). Also he has to prepare the information about the resources (yearly budget during the planning horizon, present and future available assets and initial inventory).

Finally, he has to prepare information on the production costs (construction, retirement, modernization, maintenance, and operations), and production limits. A list of all the data input requirement for the model is presented in appendix C.

C. END GAME CONSIDERATIONS

Ideally, we should set our planning horizon to a number of years T, such that the set of decisions will not change whether the model uses an infinite horizon or a horizon set at the T value (Walker 1995) . But we have limited information for the years ahead, and the single thing we know for certain is that the inputs to our model requirements, policy, and resources will change, and hence our solution will change. The reason is that the future social utility of a military defense program, and its heavy associated investment, depends on the state of a changing world.

So, the search of this 'theoretical' T value will not be our concern here. The planning horizon length will be a 'policy decision,' and what we need is a way to lessen the effect that meeting long term, and hence uncertain, requirements will have on the model's most immediate decisions. A high discount rate places a greater emphasis on the immediate cost of decisions and reduces the effect of decisions in later years. However, our discount rate is not under the analyst's control. It is fixed by the Office of Management and Budget (OMB Circular A-94, 1994). Therefore, as a way to get this effect we include in our model a single scalar (≤ 1.0) that affects the penalties portion of the objective function. Values of this parameter less than 1.0 cause the effect of not meeting the model requirements to decrease as we move farther from the first years of the planning horizon.

D. ECONOMIC CONSIDERATIONS

GOVERNMENT INSTRUCTIONS

In general, previous research on this problem did not explicitly address the economic considerations related to the cost data used as model input. But the Office of Management and Budget (OMB Circular A-94, 1994) issues very precise instructions on this subject. It requires that any analysis used to support government decisions to initiate, renew, or expand programs or projects which consider costs extended for three or more years to consider the capital cost in its economic evaluations, and must follow these economic instructions:

INFLATION

The economic analysis should use real or constant-dollar values, i.e. by measuring cost in units of stable purchasing power. The reason is that future inflation is highly uncertain, and whenever possible must be avoided in the models.

DISCOUNT RATE

The value of money will change; in fact our model falls into the category of a cost-effectiveness analysis model, as defined by OMB Circular A-94, because it does not allow an equivalent dollar value to be considered for the benefits provided by the alternatives under consideration, and as a consequence we must consider in the model as our discount rate "the real Treasury borrowing rate on marketable securities of comparable maturity to the period of analysis."

Those discount-rate figures are published annually by the OMB Publications Office and can be retrieved at "http://www.whitehouse.gov/WH/EOP/omb." Since March 1996, and for the normal planning horizon of our model, the discount rate has been set at 2.9 %. This value, combined with any known price change trend, should be used when filling cost tables in the model interface.

The reason for considering the value of capital costs in the model is that the Government in order to maximize the economic well-being of the nation as a whole, must consider the possible return of that capital if the funds were left in the private sector.

LEARNING CURVE EFFECT

Another economic consideration, not included in the OMB circular, is the learning curve effect that impacts the cost of building new assets. These costs are not linear: the first units are the most expensive and the prices diminish for successive units. This effect cannot be included in the model because it would convert the problem into a non-linear mixed integer program and we don't have any efficient solvers for problems of this type and size.

Another way to consider the learning curve effect is the following: A work force may experience a learning curve effect on a new production line and require a slower production rate during the first production years of a production campaign. The maximum-year production limit should be smaller for the earlier years of the campaign. This effect can not be incorporated into the current form of our model because the production limits are constant throughout the planning horizon.

COST CHANGES OVER TIME

If historical data on the rate of increase of prices of a given asset is available it can be included in the model input, without inflation, and discounted with the appropriate discount rate.

FORCING A CONSTRUCTION CAMPAIGN

Sometimes the decision maker is confronted with the possibility of accepting a 'bargain construction campaign' that offers certain fixed years of a given fixed production at a facility for what it is supposed to be very good price. To evaluate the benefit of accepting this type of 'bargain', the user can specify for a production line a fixed pair of opening and closing years and a minimum and maximum year production set. The results of the model will make clear if accepting the preset conditions (a given starting and ending production campaign with a fixed number of assets to build) is going to improve the solution. While our intuition may suggest that a more economical construction campaign will always be accepted, the interactions of the problem are so complex that the model is needed to evaluate the benefits (if any).

VII. FURTHER MODEL POSSIBILITIES

A. ROLLING HORIZON OPTION

Certainty about the future is ideal for decision making, but we seldom enjoy certainty. There is uncertainty about planning cost factors and technology changes, and uncertainty also exists in the model requirements. All economic activity is subject to change. Political, technological, and economic factors may change our future equipment requirements.

These considerations may, occasionally, force us to use the model in the following way: Replacement of units is computed over the entire planning horizon but only the immediate decisions are implemented. A dynamic rather than a static replacement policy must be put into effect. This will necessitate the adoption of a rolling schedule. As the schedule rolls forward in time new requirements and data are appended to the model, so that the length of the planning horizon is maintained at the desired number of years. Those decisions appearing later in the schedule will be reconsidered by the optimization program, now with updated information, because they are inside the new planning horizon. Again, only immediate replacement decisions are implemented each time the schedule is rolled forward and inputs to the model are updated. The time span between reoptimizations is a policy decision that will differ with the problem being treated.

B. PERSISTENCE IN THE SOLUTION

The rolling horizon introduces the concept of persistence; that is, the penalizing of changes to already committed construction campaigns when the model is rerun in each updated rolled horizon. This consideration is not included in our model and is a proposed enhancement.

C. MODEL APPLICABILITY TO PRIOR NPS THESES

This model, being an almost direct translation of PHOENIX, is more general than previous models developed in other NPS theses in this area. Nevertheless, no two problems have the same requirements, and some previous works have special conditions. For instance, the Drash model considers as a possible fate for its Maritime Patrol Aircraft that they be transferred to the Reserve Fleet. The Dundas model does not consider cohorts, but rather categorizes its assets by cumulative flight hours. It is possible that a modified version of some of those scenarios can be accommodated in our model.

D. FUTURE OF THE MODEL

Although it is likely that many scenarios can be handled by simply adapting the data input structure, it is easy to imagine many other scenarios that the model, in its present form, cannot support. If modifications are deemed necessary, the open design, with its three separate parts, Input to Excel, GAMS file, and Output to Excel, will make changes and additional improvements possible.

VII. CONCLUSIONS

A. SUMMARY OF CONTRIBUTIONS

This model and its spreadsheet interface respond to a pervasive request by previous theses: the need for a user interface and a graphical analysis tool for equipment replacement problems. The model solves, under the proper assumptions, the Equipment Replacement Problem providing the following features:

- Use of elastic constraints to prevent unfeasible solutions;
- Interactive change of the penalty weights to allow the input of user judgment in the construction of a satisfactory solution; and
- Graphic output representation and storing of different solutions to facilitate their assessment and comparison.

Computing details are hidden from the user, who interacts only with the spreadsheet. Also the user does not have to build the model. The combination of a generic model and the visual programming capability of the spreadsheet provides the user with a tool to execute more complete, complex and sophisticated analysis.

B. COMPARING THIS MODEL WITH PHOENIX

Compared to PHOENIX, our model incorporates the following changes: The user does not input a two-value set for opening and closing years of production lines, rather he specifies only the first feasible opening year. The actual opening and closing years will be decided by the optimization process and by the limits on the total line production. We do not consider the possibility of interdependence among some production campaigns.

C. POSSIBLE ENHANCEMENTS

As possible enhancements to the model we may consider adding the following:

- "Two categories of monies," consisting of adding to the model separate budgets for Procurement and for Operation and Maintenance;

- "Second-Hand Market Value," adding as one of the possible fates of our assets their sale to third parties with a salvage value that diminishes with the age of the asset;
- "Different Levels of Modernization," adding the option of different modernization programs with different costs and effects on the asset's maximum life;
- "Persistence," penalizing changes in actions already committed; and
- "Leasing" as a source of assets, an option which conveys a quite complex set of economic considerations (see OMB Circular A-94 and Dundas 1996).

C. FINAL COMMENTS

The operations research approach uncovers the relationship between the economic dimension of the problem and meaningful indicators of military performance. The military executive can get a clear picture of what has to be sacrificed in one area in order to gain something in another. Gains and losses are not measured in common units but in those indicators that makes sense for the military expert making the decisions. The process of trade-off comparisons obviously facilitates a final judgment. Decision makers have access to a large amount of impartial information about the trade-offs involved in their conflicting objectives. The final decision remains a matter of judgment, but the basis to judge has been improved, and with that the quality of the decision.

APPENDIX A : MATHEMATICAL FORMULATION OF THE MODEL

The formulation for the mixed-integer programming model is presented in a notation that is consistent with the GAMS formulation.

Index Use

t, t' ~ planning year
m ~ mission
p ~ production line
a, a' ~ asset
u, u' ~ cohort year (year of manufacture)

Index Sets

Λ_{au} ~ set of assets 'a' that belong to cohort 'u'
Π_{pa} ~ set of production lines 'p' that can produce asset 'a'
Θ_{am} ~ set of assets 'a' that can perform mission 'm'
Ω_{ta} ~ set of assets 'a' that are considered high technology in year 't'
$\Psi_{t\Lambda}$ ~ subset of Λ that is operative in year 't' (has joined the fleet and is under maximum service life).
$\Phi_{t\Lambda}$ ~ subset of Λ that can be retired or modernized in year 't' (has joined the fleet and is over minimum service life)

Data Sets

$\overline{b_t}$ budget for year t (upper limit)
$\underline{b_t}$ budget for year t (lower limit)
$\overline{cp_p}$ cumulative production in production line p (upper limit)
$\underline{cp_p}$ cumulative production in production line p (lower limit)
fc_p fixed cost of opening production line p
$\overline{fs_{tm}}$ required force size for mission m in year t (upper limit)
$\underline{fs_{tm}}$ required force size for mission m in year t (lower limit)
ft_{tm} required fraction of assets in a mission with high technology consideration
fy_p fixed yearly cost for keeping line p open
lag_a years between when the new asset is paid for and the year it joins the fleet
ma_{tm} required average age of assets in year t for mission m
oc_{ta} O & M cost of asset a in year t
pc_{ta} production cost of asset a in year t
rc_{ta} retiring cost of asset a in year t
sc_{ta} modernization cost of asset a in year t
$slag_a$ years between when the modernization is paid for and the year it joins the fleet

sv_a survival fraction of assets a in a year period
$wt1_p$ number of years from starting planning to when line p can be opened
$wt2_p$ number of years from starting planning to when line p must be closed
$\overline{yp}_p$ yearly production in production line p (upper limit)
$\underline{yp}_p$ yearly production in production line p (lower limit)

Decision Variables

$X_{t\Lambda}$ Integer number of assets belonging to $\Psi_{t\Lambda}$ in operation in year t
X_{tat} Integer number of assets type a built in year t
$R_{t\Lambda}$ Integer number of assets belonging to $\Phi_{t\Lambda}$ sent to retire in year t
$S_{t\Lambda}$ Integer number of assets belonging to $\Phi_{t\Lambda}$ sent to modernize in year t
S_{tat} Integer number of assets type a belonging to $\Phi_{t\Lambda}$ that join the fleet in year t after being modernized
XY_{tap} Integer number of assets type a paid to build in year t at production line p
SY_{tap} Integer number of assets type a paid to modernize in year t at line p
$SS_{t\Lambda}$ Integer number of modernized assets joining the fleet as cohort Λ in year t.
O_{tp} Binary indicator equals one if line p is open to build new assets in year t
D_{tpa} Binary indicator equals one if line p is keep open in year t to build type a
O'_{tp} Binary indicator equals one if line p is open modernize assets in year t
D'_{tpa} Binary indicator equals one if line p is keep open in year t to modernize a

Objective Function

Minimize

$$\sum_t \Bigg(\sum_{\Psi_{t\Lambda}} oc_{t,\Lambda} X_{t,\Lambda} + \sum_a pc_{t,a} X_{t,a,t} + \sum_{\Phi_{t\Lambda}} rc_{t,a} R_{t,\Lambda} + \sum_{\Phi_{t\Lambda}} sc_{t,a} S_{t,\Lambda} +$$

$$\sum_p fc_p O_{t,p} + \sum_p \sum_a fy_p D_{t,p,a} + \sum penalties \Bigg)$$

Constraints

$$\underline{fs}_{tm} \leq \sum_{\Psi_{t\Lambda} \varepsilon \Theta_{am}} X_{t,\Lambda} \leq \overline{fs}_{tm} \qquad ,\forall t,m \tag{1}$$

$$\underline{b}_t \leq \sum_{\Psi_{t\Lambda}} oc_{t,\Lambda} X_{t,\Lambda} + \sum_a pc_{t,a} X_{t,a,t} + \sum_{\Phi_{t\Lambda}} rc_{t,a} R_{t,\Lambda} + \sum_{\Phi_{t\Lambda}} sc_{t,a} S_{t,\Lambda} +$$

$$\sum_p fc_p O_{t,p} + \sum_p \sum_a fy_p D_{t,p,a} \leq \overline{b}_t \qquad ,\forall t \tag{2}$$

$$\sum_{\Psi_{t\Lambda}\varepsilon\Theta_{am}} ma_{t,m} X_{t,\Lambda} \leq \sum_{\Psi_{t\Lambda}\varepsilon\Theta_{am}} (t-u-lag_a) X_{t,\Lambda} \qquad ,\forall t,m \qquad (3)$$

$$\sum_{\Psi_{t\Lambda}\varepsilon\Omega_{ta}} \sum_{\Psi_{t\Lambda}\varepsilon\Theta_{am}} ht_{t,a} X_{t,\Lambda} \geq \sum_{\Psi_{t\Lambda}} \sum_{\Psi_{t\Lambda}\varepsilon\Theta_{am}} ft_{t,m} X_{t,\Lambda} \qquad ,\forall t,m \qquad (4)$$

$$X_{t-1,\Lambda} sv_a - R_{t,\Lambda} - S_{t,\Lambda} + X_{t,a,t} + SS_{t-slaga,a,t-slaga} = X_{t,\Lambda} \qquad ,\forall t,\Lambda \qquad (5)$$

$$R_{t,\Lambda} + S_{t,\Lambda} \leq X_{t-1,\Lambda} \qquad ,\forall t,\Lambda \qquad (6)$$

$$\underline{cp}_p \leq \sum_t \sum_{p\varepsilon\prod_{pa}} \left(XY_{t,a,p} + SY_{t,a,p}\right) \leq \overline{cp}_p \qquad ,\forall p \qquad (7)$$

$$\underline{yp}_p \leq \sum_{p\varepsilon\prod_{pa}} \left(XY_{t,a,p} + SY_{t,a,p}\right) \leq \overline{yp}_p \qquad ,\forall p,t \qquad (8)$$

$$\sum_u S_{t,\Lambda} = SS_{t,a,t} \qquad ,\forall t,a \qquad (9)$$

$$\sum_{p\varepsilon\prod_{pa}} XY_{t,a,p} = X_{t,a,t} \qquad ,\forall t,a \qquad (10)$$

$$\sum_{p\varepsilon\prod_{pa}} SY_{t,a,p} = SS_{t,a,t} \qquad ,\forall t,a \qquad (11)$$

$$\sum_a D_{t,p,a} \leq \sum_{t'<t} O_{t',p} \qquad ,\forall t,p \qquad (12)$$

$$\underline{yp}_p \sum_a D_{p,t,a} \leq XY_{t,a,p} \leq \overline{yp}_p \sum_a D_{p,t,a} \qquad ,\forall t,p \qquad (13)$$

$$\sum_a D_{p,t,a} \leq \sum_a D_{p,t-1,a} + O_{t,p} \qquad ,\forall t,p \qquad (14)$$

$$\sum_t O_{t,p} \leq 1 \qquad ,\forall p \qquad (15)$$

$$\sum_{t<wt1_p} O_{t,p} = 0 \qquad ,\forall p \qquad (16)$$

$$\sum_{t > wt2_p} O_{t,p} = 0 \qquad ,\forall p \qquad \textbf{(17)}$$

$$\sum_a D'_{p,t,a} \le \sum_{t'<t} O'_{t',p} \qquad ,\forall t,p \qquad \textbf{(18)}$$

$$\underline{yp}_p \sum_a D'_{p,t,a} \le XY_{t,a,p} \le \overline{yp}_p \sum_a D'_{p,t,a} \qquad ,\forall t,p \qquad \textbf{(19)}$$

$$\sum_a D'_{p,t,a} \le \sum_a D'_{p,t-1,a} + O'_{t,p} \qquad ,\forall t,p \qquad \textbf{(20)}$$

$$\sum_t O'_{t,p} \le 1 \qquad ,\forall p \qquad \textbf{(21)}$$

$$\sum_{t < wt1_p} O'_{t,p} = 0 \qquad ,\forall p \qquad \textbf{(22)}$$

$$\sum_{t > wt2_p} O'_{t,p} = 0 \qquad ,\forall p \qquad \textbf{(23)}$$

$$\sum_t \left(O_{t,p} + O'_{t,p}\right) \le 1 \qquad ,\forall p \qquad \textbf{(24)}$$

$$\sum_a (D_{p,t,a} + D'_{t,p,a}) \le 1 \qquad ,\forall t,p \qquad \textbf{(25)}$$

$$X_{t,\Lambda}, X_{t,a,t}, R_{t,\Lambda}, S_{t,a,t}, S_{t,\Lambda}, XY_{t,a,p}, SY_{t,a,p}, SS_{t,\Lambda} \in \{int\}$$

$$D_{t,p,a}, D'_{t,p,a}, O_{t,p}, O'_{t,p} \in \{0,1\}$$

Related to the production line constraints, we use a set of equations for the build decisions (12 to 17) and a parallel set of equations for the modernization decisions (18 to 23). Although it can be simplified we keep it that way to be consistent with a GAMS formulation.

DESCRIPTION OF THE CONSTRAINTS

(1) Track fleet size by mission for all of the planning horizon, elastic.

(2) Keep budget between limits each year of the planning horizon, elastic.

(3) Keep average age of assets under desired limit, elastic.

(4) Keep high technology proportion in each mission over its desired limit, elastic.

(5) Inventory constraint, accounts for inflow and outflow of each asset cohort each year.

(6) Ensures that the number of modernized and retired assets is not greater than those available.

(7) Keep upper and lower limit of total cumulative production on a given production line, elastic.

(8) Keep upper and lower limit of yearly production on a given production line, elastic.

(9) Compute the number of assets of given type that leave the fleet to be modernized, by year.

(10) Compute the number of new assets of a type being built on all possible production lines, by year.

(11) Account for all assets being modernized on all possible production lines for a given year.

(12,18) A line will not remain open to build (modernize) unless it was open to build (modernize) before.

(13,19) Establish a limit on total assets built (modernized) in a line that remains open a given year.

(14,20) A line remains open only if it was open the previous year or if it was opened this year.

(15,21) Do not open a line more than once in a planning horizon.

(16,22) Do not open a line before the required delay in years.

(17,23) Do not keep a line open after the upper limit of years.

(24) A line can be opened to build or to modernize but not for both tasks along the planning horizon.

(25) In a given year a line can remain open to build or to modernize but not for both tasks.

APPENDIX B : WALK-THROUGH OF AN EXAMPLE ANALYSIS

In this appendix the use of the system to analyze an example problem is demonstrated with a sequence of 28 screens shots of the graphical user interface. The example shows the modernization of two assets types over a planning period of ten years using three production lines. The captions describe how a user enters data, launches the optimization and analyzes the solution. The iterative analysis process of solution analysis, feedback to the model and reoptimization is also described.

<u>Presentation of the application screens</u>

Figures 1,2, 3, 9, 10

<u>Data input screens to the application (partial)</u>

Figures 4, 5, 6, 7, 8

<u>Initial set of constraints penalty weights to optimize</u>

Figure 11

<u>Analysis of the output</u>

Figures 12, 13, 14, 15, 16

<u>New set of constraint penalty weights to optimize</u>

Figure 17

<u>Analysis of the new solution output</u>

Figures 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28

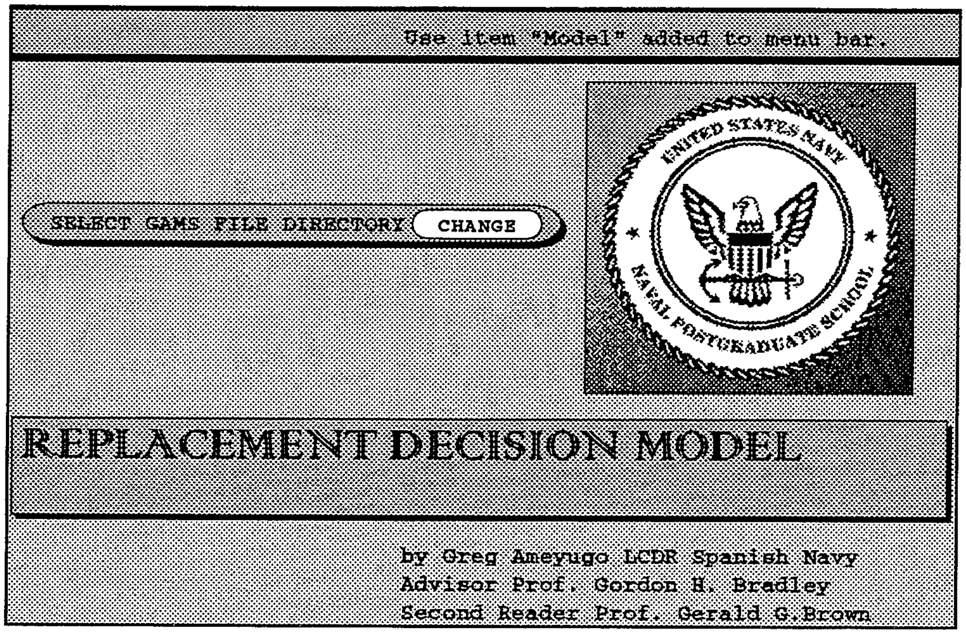

Figure 1 The first screen in the EXCEL application prompts the user to specify the location of the GAMS files. A new menu item has been added to the Excel upper menu bar (see next figure); from there the user can move through the application.

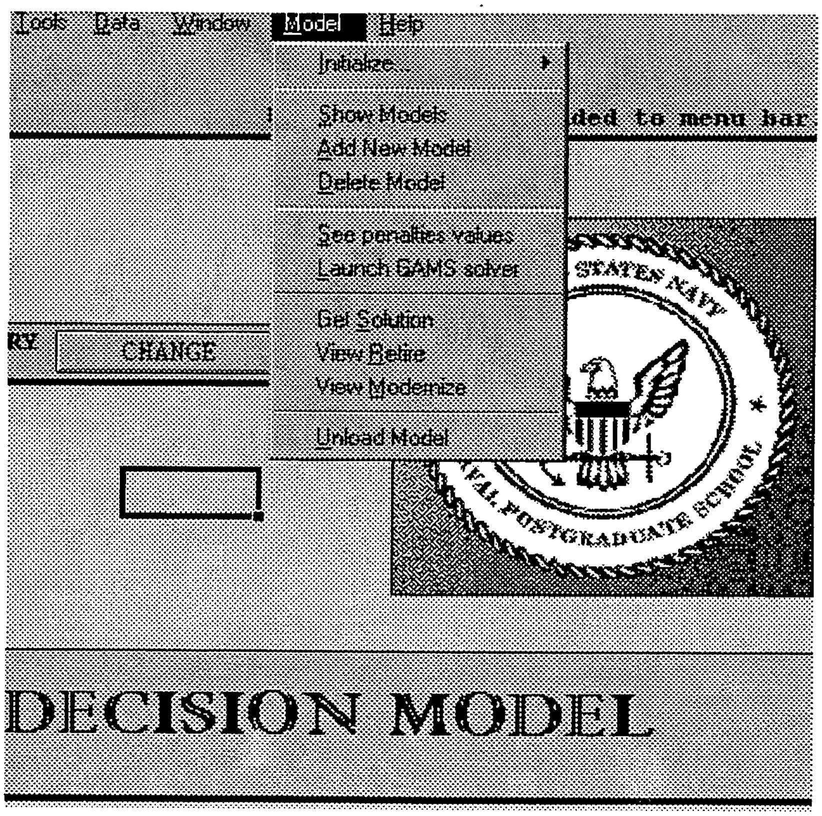

Figure 2 The menu items allow the user (from top to bottom) to: change the GAMS file location, see which saved models are available,(and load one , original or copy), add , delete any existing model, see the current penalties, launch GAMS, read the solution, and as part of the solution read the assets to retire or modernize, and finally make this menu disappear and unload the application.

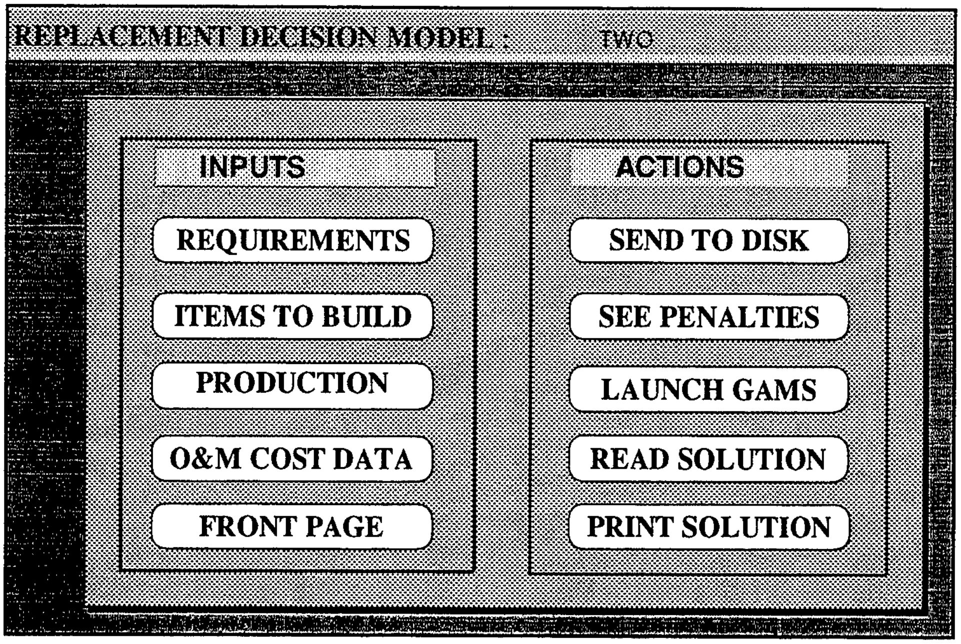

Figure 3 When the user creates a new model he is prompted for a name for this new model and is shown this screen called the Control Screen. From here the user is able to enter model data using left column buttons and to solve the model, interact with it, and finally print the solution using the right column buttons. The input buttons lead the user through successive screens: REQUIREMENTS (5 screens), ITEMS TO BUILD (7 screens), PRODUCTION (2 screens), and O&M COST DATA (1 screen).

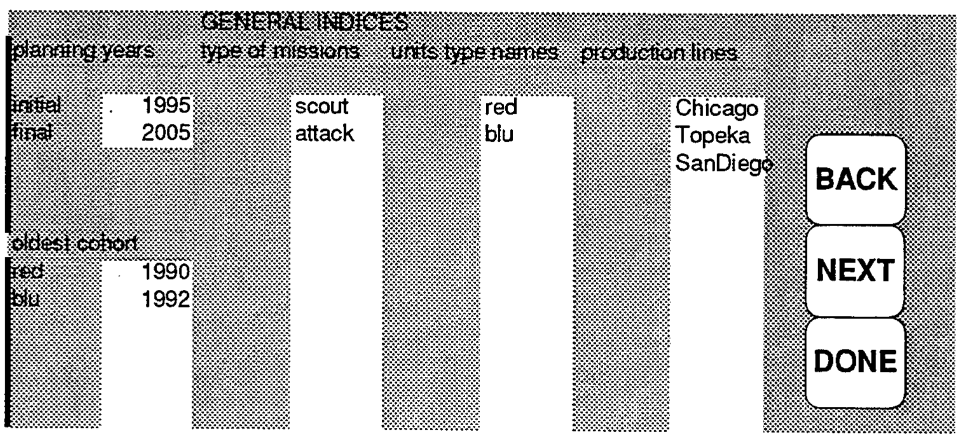

Figure 4 In the first screen prompted by the REQUIREMENTS button, the user enters the values used to create indices for the other input screens. The other input screens in this area can be accessed in succession by clicking the NEXT button; the DONE button brings the user back to the Control Screen.

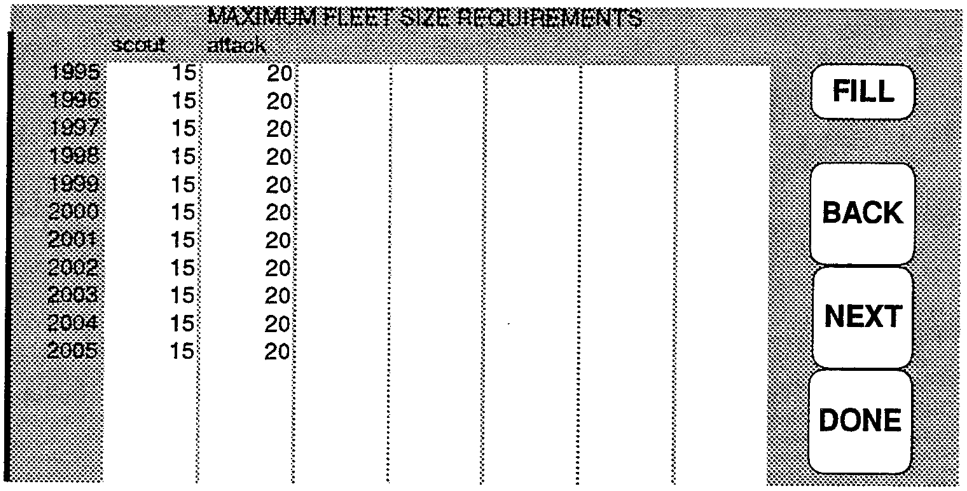

Figure 5 Shown here are the scout and attack mission maximum fleet sizes for planning horizon 1995-2005. The user is lead through similar screens to enter minimum fleet size, average age, technological split, minimum and maximum budget. The values in the table can be entered directly or the button FILL extends the first year values modified with a linear rate of increase / decrease that the user selects.

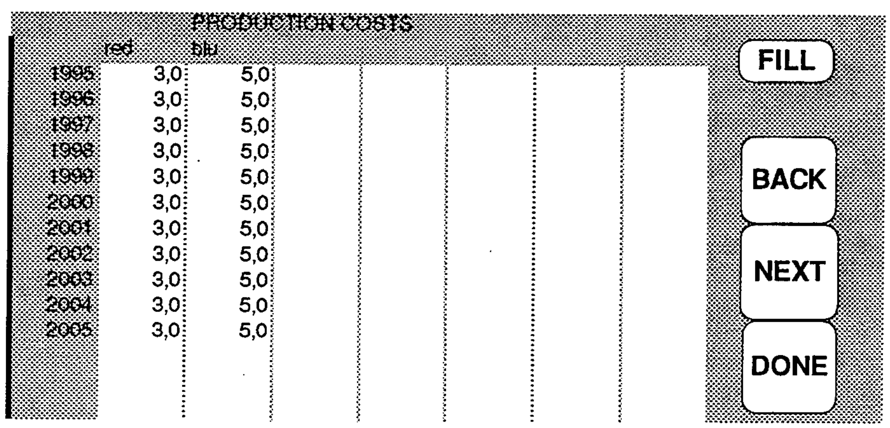

Figure 6 From the Control Screen button ITEMS TO BUILD the user is lead through 7 screens to enter the information related to all the assets that are to be considered as candidates in the solution. For example, this screen is used to enter asset production costs. Monies are in millions of dollars.

LIMITS ON UNITS PRODUCED

max total pr		min total pr		max year pro		min year pro		PRODUCTION LINES DATA
	MAXTP		MINTP		MAXYP		MINYP	
Chicago	12	Chicago	6	Chicago	3	Chicago	2	
Topeka	14	Topeka	8	Topeka	3	Topeka	2	
SanDieg	12	SanDieg	6	SanDieg	3	SanDieg	2	

BACK

NEXT

DONE

FIXED COST IN PROD. LINES | WAITING TIME

incurred once each year	oper			open possible		closing mandatory	
	FIXOPEI		FIXYR		OPENIN		CLOSING
Chicago	2	Chicago	1	Chicago	1	Chicago	10
Topeka	2	Topeka	1	Topeka	3	Topeka	10
SanDieg	2	SanDieg	1	SanDieg	3	SanDieg	10

Figure 7 From the Control Screen button PRODUCTION, the user is lead through 2 screens to enter production line data into the model. The MINTP column contains the minimum total cumulative production at the production lines being considered. For instance, this minimum value is 8 for Topeka.

OPERATIONS AND MAINTENANCE COST | DISK | DONE

	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
red.1990	0,3	0,3	0,3	0,3	0,3	0,4	0,4	0,4	0,4	0,4	0,4
red.1991	0,3	0,3	0,3	0,3	0,3	0,3	0,4	0,4	0,4	0,4	0,4
red.1992	0,3	0,3	0,3	0,3	0,3	0,3	0,4	0,4	0,4	0,4	0,4
red.1993	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,4	0,4	0,4
red.1994	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,4	0,4	0,4
red.1995	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,4	0,4	0,4
red.1996		0,2	0,2	0,2	0,2	0,3	0,3	0,3	0,3	0,3	0,3
red.1997			0,2	0,2	0,2	0,2	0,3	0,3	0,3	0,3	0,3
red.1998				0,2	0,2	0,2	0,3	0,3	0,3	0,3	0,3
red.1999					0,2	0,2	0,2	0,3	0,3	0,3	0,3
red.2000						0,2	0,2	0,2	0,3	0,3	0,3
red.2001							0,2	0,2	0,2	0,3	0,3
red.2002								0,2	0,2	0,3	0,3
red.2003									0,2	0,2	0,2
red.2004										0,2	0,2
red.2005											0,2
blu.1992	0,1	0,1	0,1	0,1	0,2	0,2	0,2	0,2	0,2	0,2	0,2
blu.1993	0,1	0,1	0,1	0,1	0,2	0,2	0,2	0,2	0,2	0,2	0,2
blu.1994	0,1	0,1	0,1	0,1	0,2	0,2	0,2	0,2	0,2	0,2	0,2
blu.1995	0,1	0,1	0,1	0,1	0,2	0,2	0,2	0,2	0,2	0,2	0,2
blu.1996		0,1	0,1	0,1	0,1	0,1	0,2	0,2	0,2	0,2	0,2
blu.1997			0,1	0,1	0,1	0,1	0,2	0,2	0,2	0,2	0,2
blu.1998				0,1	0,1	0,1	0,2	0,2	0,2	0,2	0,2
blu.1999					0,1	0,1	0,2	0,2	0,2	0,2	0,2
blu.2000						0,1	0,2	0,2	0,2	0,2	0,2

Figure 8 From the Control Screen button O & M COST DATA, the user is shown this screen to enter Operation and Maintenance cost information. The values can be entered directly or through the DISK button from another spreadsheet file. The figure is a partial view of the table. The row label contains all possible cohorts for each asset being considered.

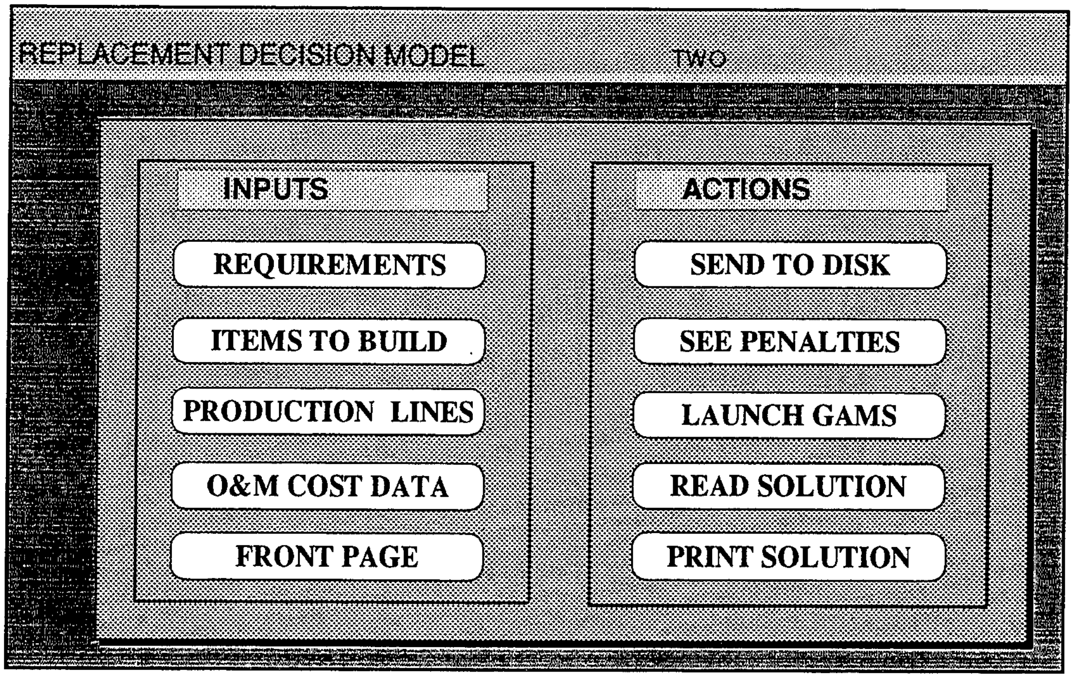

Figure 9 Once all four input data items in the left column of the Control Screen have been entered, the action buttons on the right can be used. The SEND TO DISK button should be used first to save the input data.

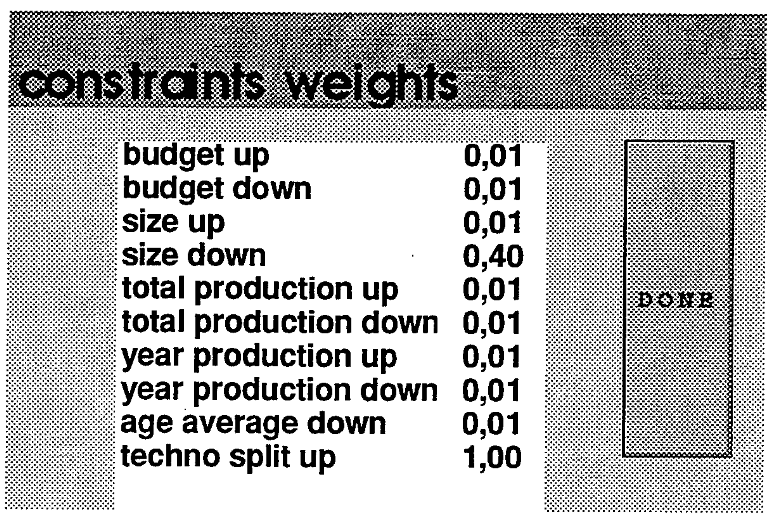

Figure 10 The SEE PENALTIES button presents the penalties for all the constraints. The default values of 0.01 for all penalty values can be modified here or on the solution screens shown below. We are going to start with a couple of these values set to values different than the default to get an initial solution that looks somewhat reasonable. We make the "size down" penalty equal 0.4 and the "techno split up" equal to 1 (e.g., the upper penalty for constraint (4)).

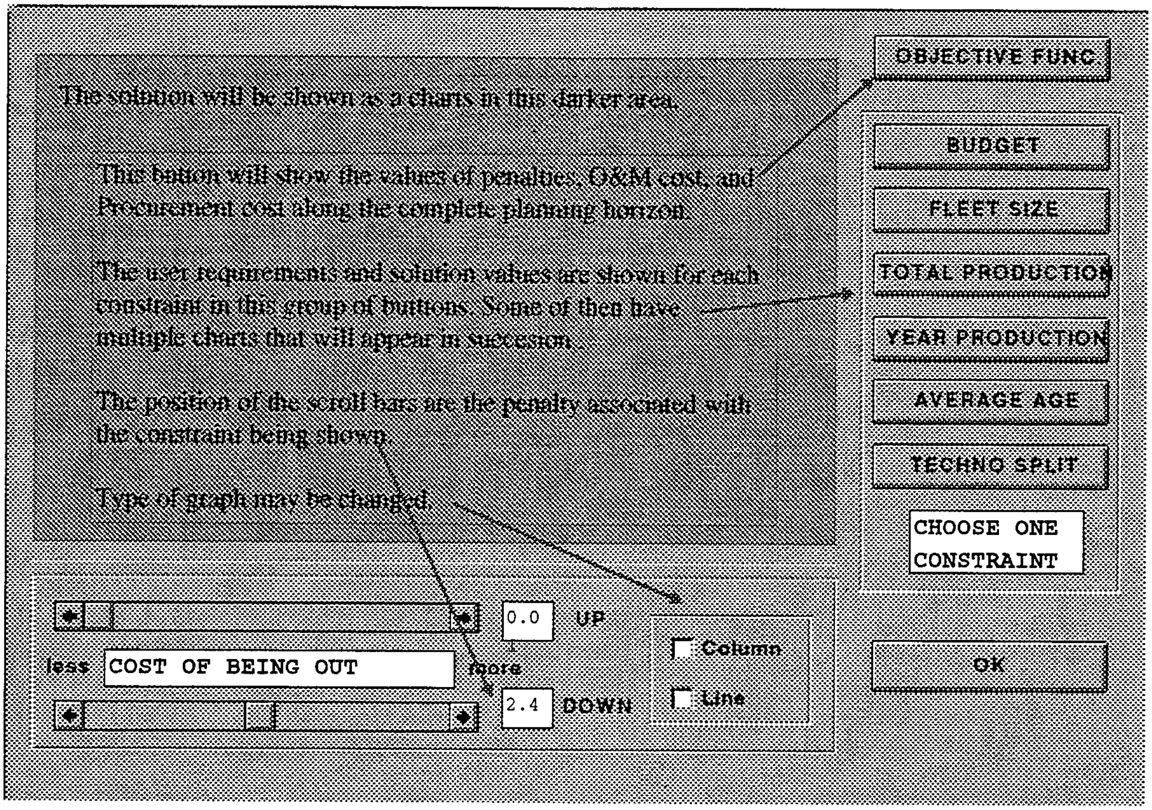

Figure 11 From the Control Screen the user begins the optimization using the LAUNCH GAMS button. After the optimal solution (with the current set of penalty weights) has been constructed and written to the disk, the optimization program reports that the optimization is complete and returns control to the spreadsheet. The user selects the READ SOLUTION button that presents the solution in graphical form. As the user analyzes the solution by viewing the complete set of screens, he can use the scroll bars to modify the penalty weights for the constraint on the screen. This changes the relative importance of that constraint's violations and is the way to enter user judgment.

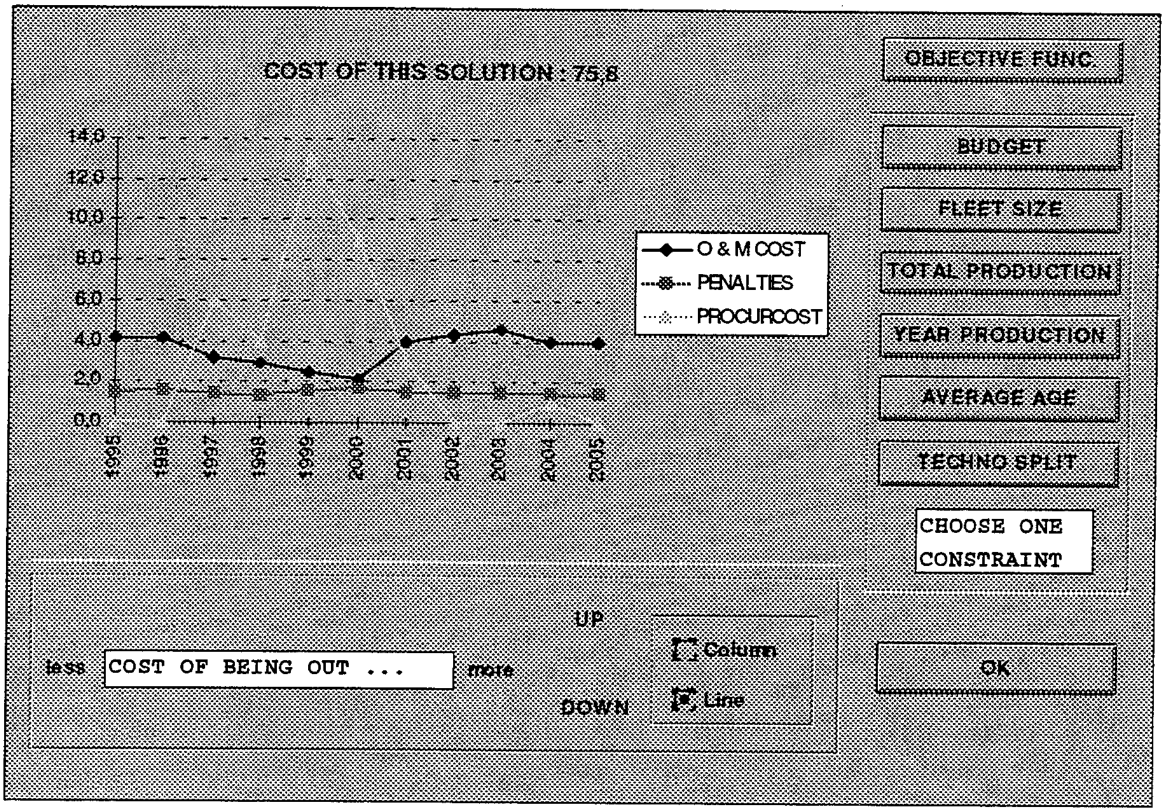

Figure 12. For a problem of this size the optimization takes only a few seconds and the READ SOLUTION button presents the set of screens containing the solution. This screen shows that the cost of the solution is 75.8 million, and that the penalties incurred are evenly distributed over the planning horizon. From this screen the user can use the buttons on the right to view the values of the solution for the six constraint types in any order, or come back to this screen using the OBJECTIVE FUNC. button.

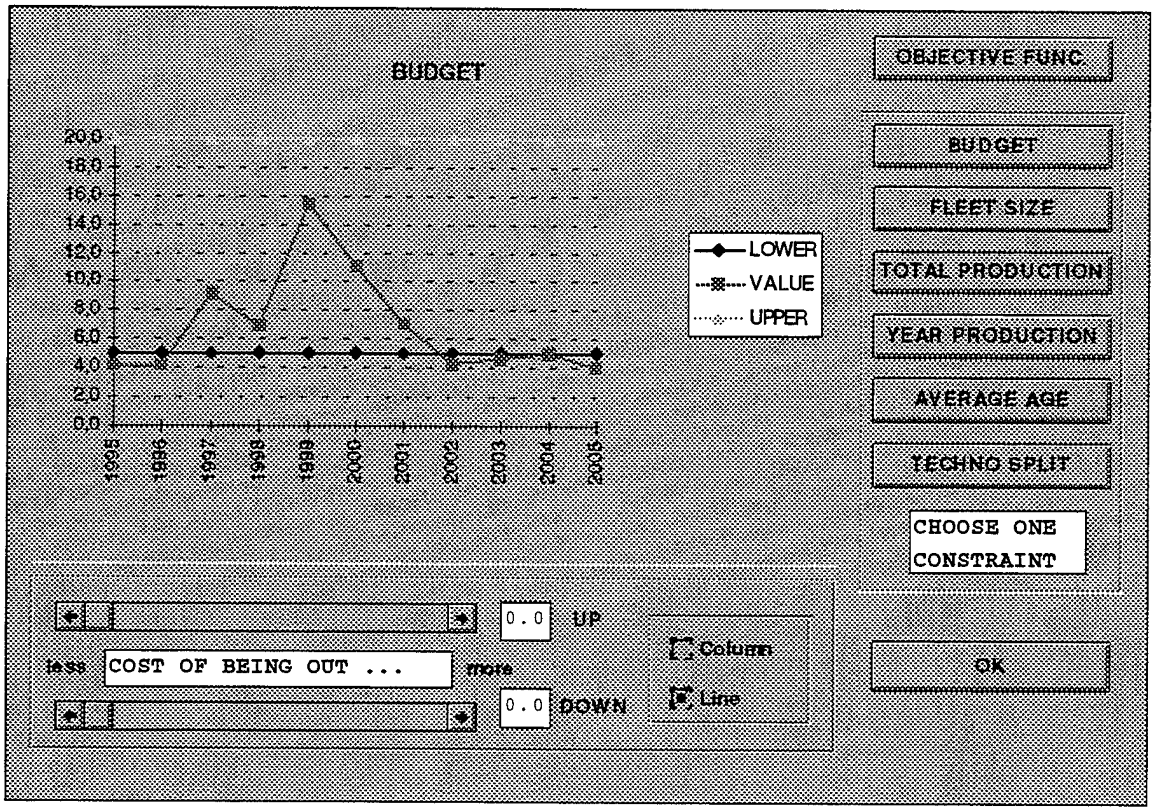

Figure 13 This figure shows the budget expenditure along the planning horizon. The penalty weights for these constraints (one for each year of the planning horizon) are so low (the default values) that the minimum budget constraint is slightly violated for several years.

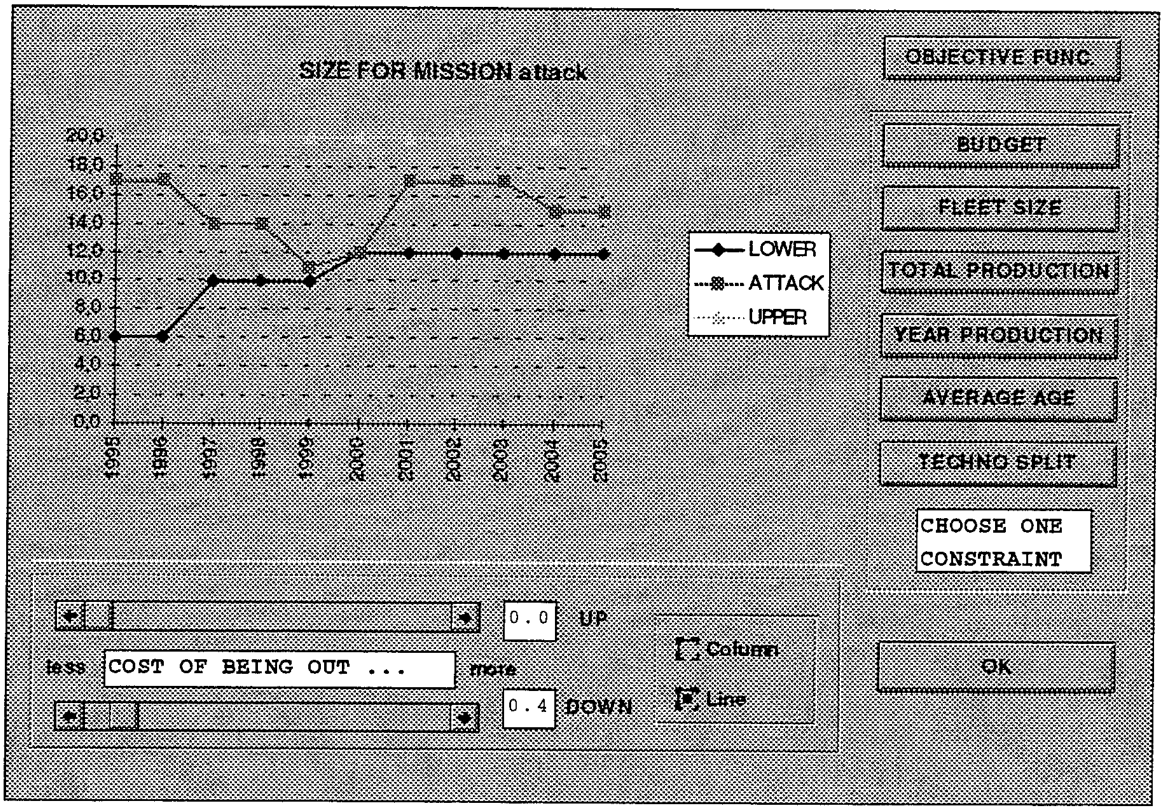

Figure 14 This is one of the screens for the FLEET SIZE constraints. The size of the fleet, for mission attack, is well inside limits. By clicking again on the FLEET SIZE button we can check limits for mission scout. Observe that the position of the lower scroll bar is 0.4, the value that was used for a lower penalty in the optimization.

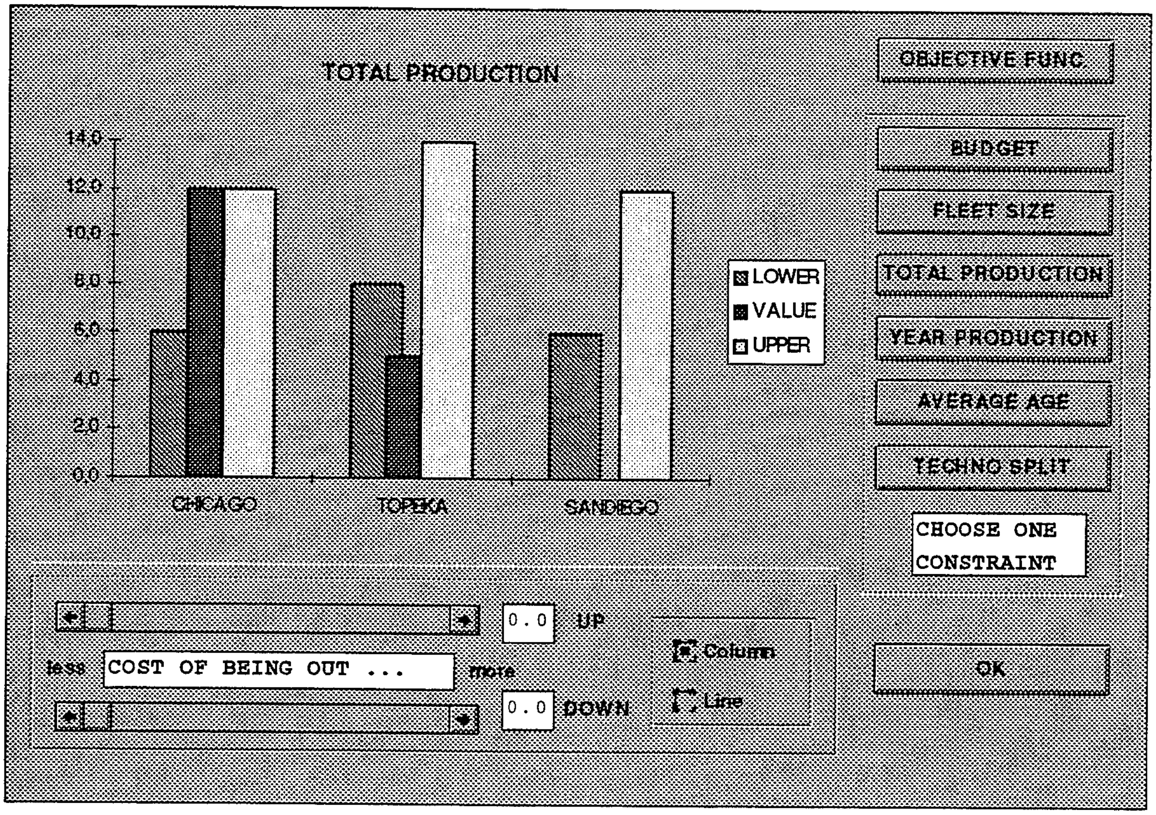

Figure 15 This is the screen for the TOTAL PRODUCTION constraints. Notice that the default for this screen is a column graph. We have both Chicago and Topeka scheduled for production but Topeka is producing under its lower limit and that is an unwanted situation. So we are not yet satisfied with the solution. We have to proceed with the iterative process of changing the penalty weights for constraints with unsatisfactory values (like this one), solving the problem again and analyzing the new solution. The process eventually ends when we arrive at a solution whose values are acceptable for all six constraints.

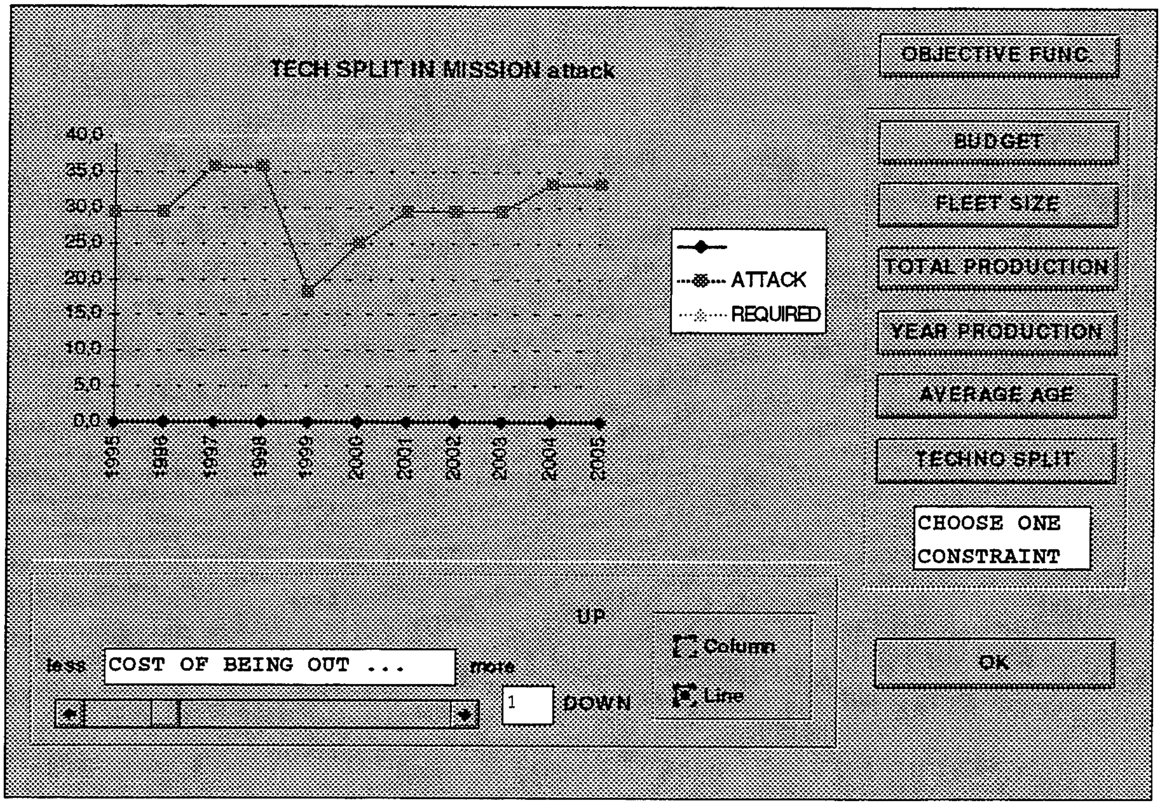

Figure 16 This is one of the screens for the TECHNO SPLIT constraints. The values are not above the desired minimum level even though we launched the solver with an initial value of 1.0 (observe the scroll bar position). That means that the penalty weight is not enough to reach a satisfactory value in this constraint and that we will need a larger penalty weight. As we will see below we need to increase this weight up to 4.6 in our search for a good solution.

constraints weights

budget up	1,10
budget down	0,30
size up	0,60
size down	4,70
total production up	0,01
total production down	2,40
year production up	0,01
year production down	0,01
age average down	1,00
techno split up	4,60

DONE

Figure 17 Following the iterative process described in the previous figures, after four or five iterations (each iteration takes less than a minute), the user reaches the set of penalty weights shown here.

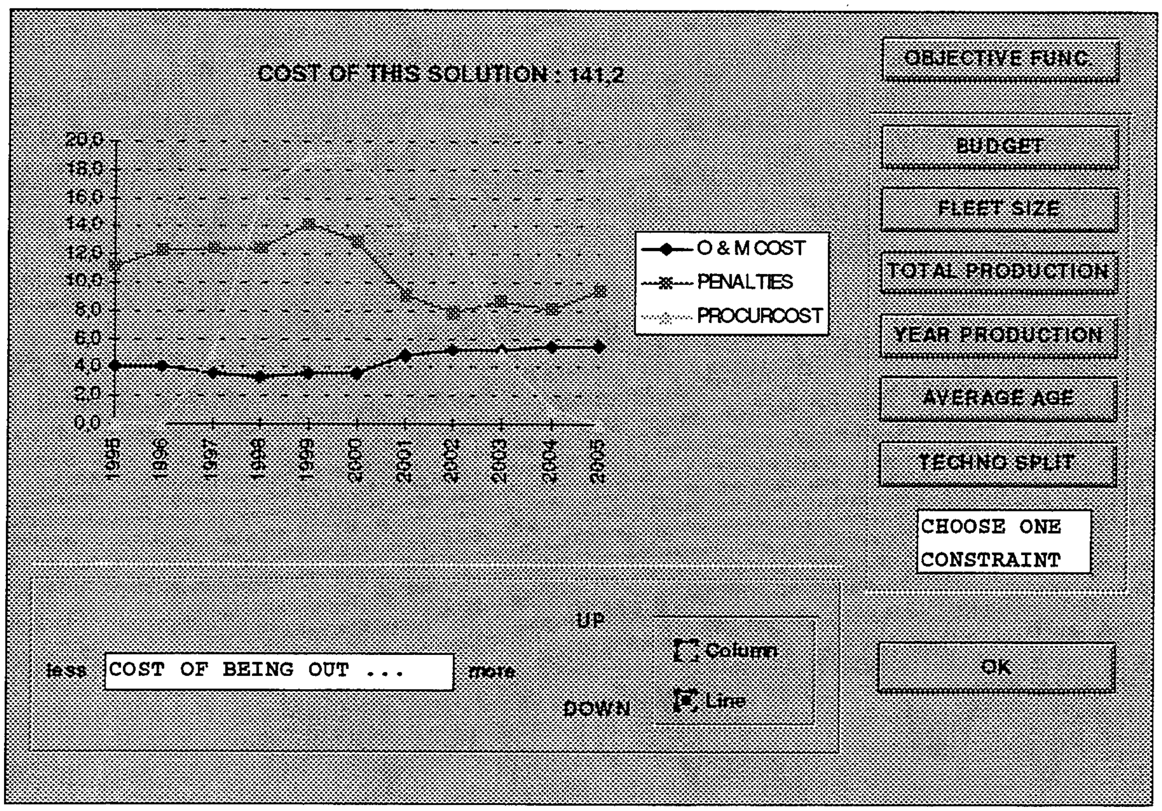

Figure 18 The solution produced with the penalty weights shown in the last figure costs 141.2 million. The user can see that the O&M cost is more or less level along the planning horizon and that the penalties have a bigger value in the first half than in the second, meaning that we are meeting our constraints better after the year 2000.

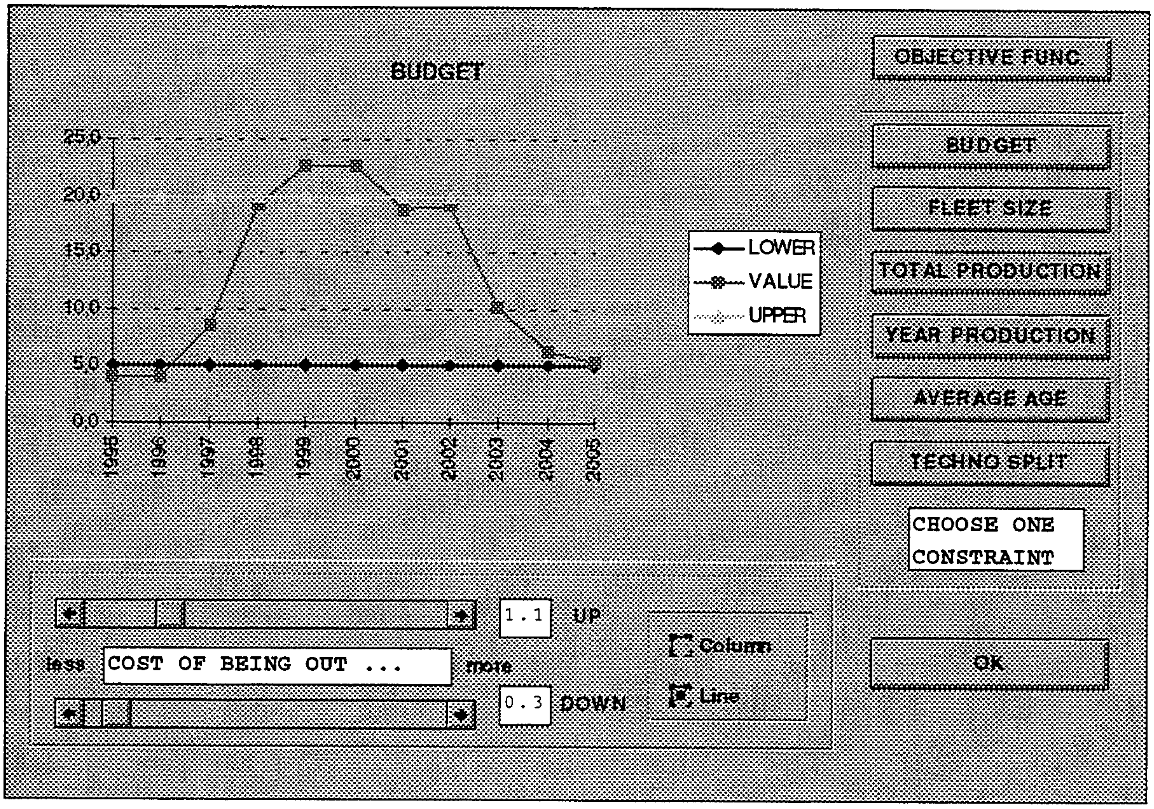

Figure 19 In the years 1999 and 2000 we are over the maximum budget value. We could increase the weight in the upper scroll bar and continue the search for a better solution or, as decision makers, we may consider this level of constraint violation acceptable.

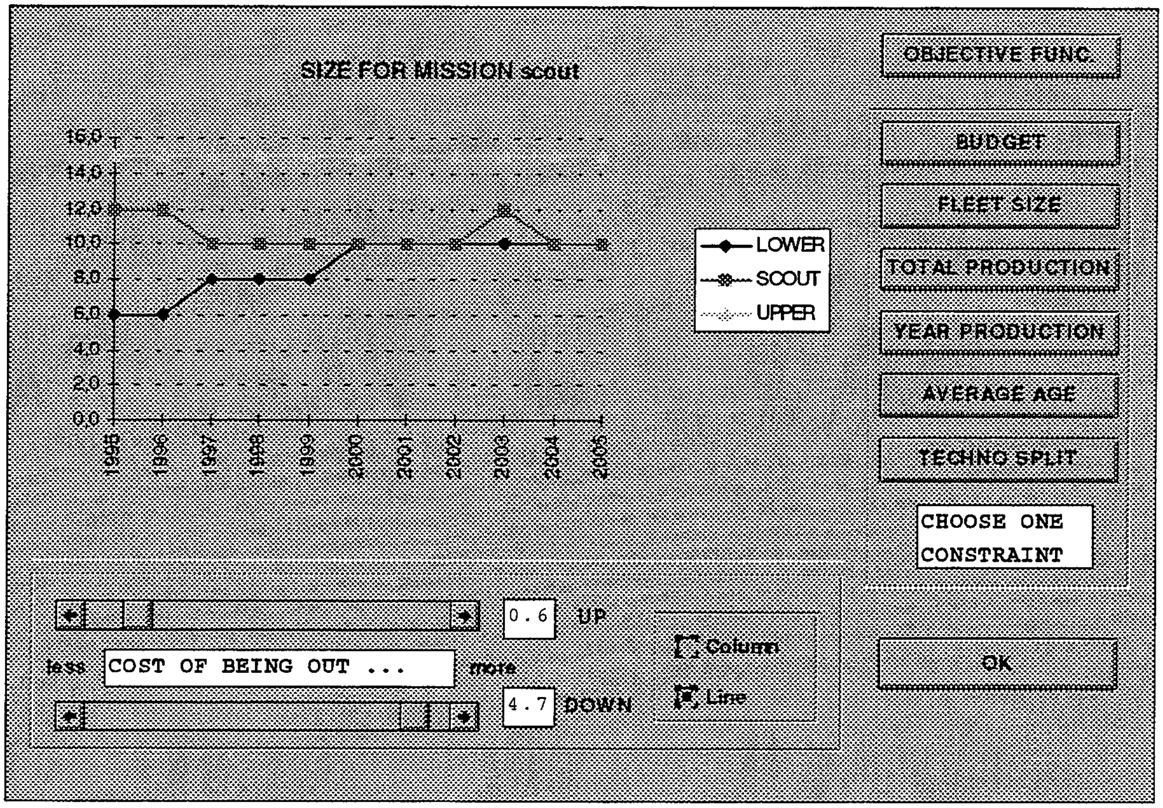

Figure 20 The values for both fleet sizes is between limits, here the scout mission fleet is shown. To see the attack mission fleet values we have to click again on the FLEET SIZE button.

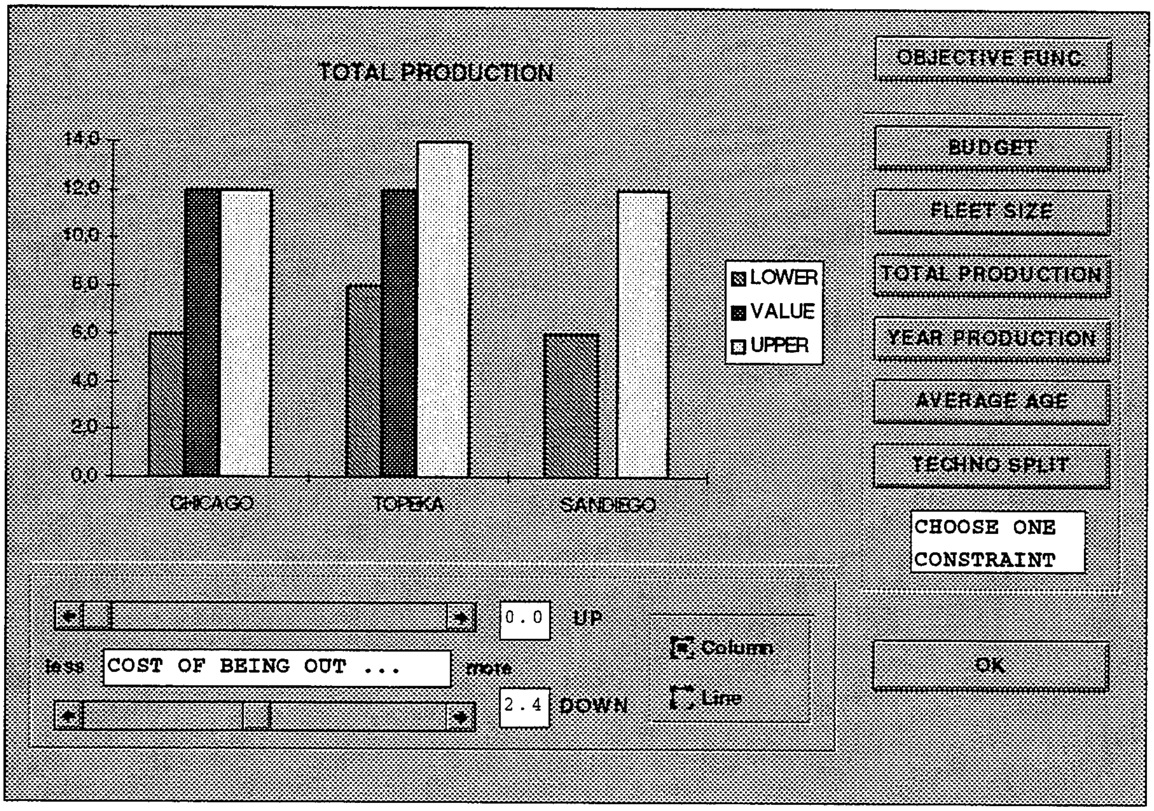

Figure 21 Total production values are inside limits, and we have scheduled the use of Chicago and Topeka.

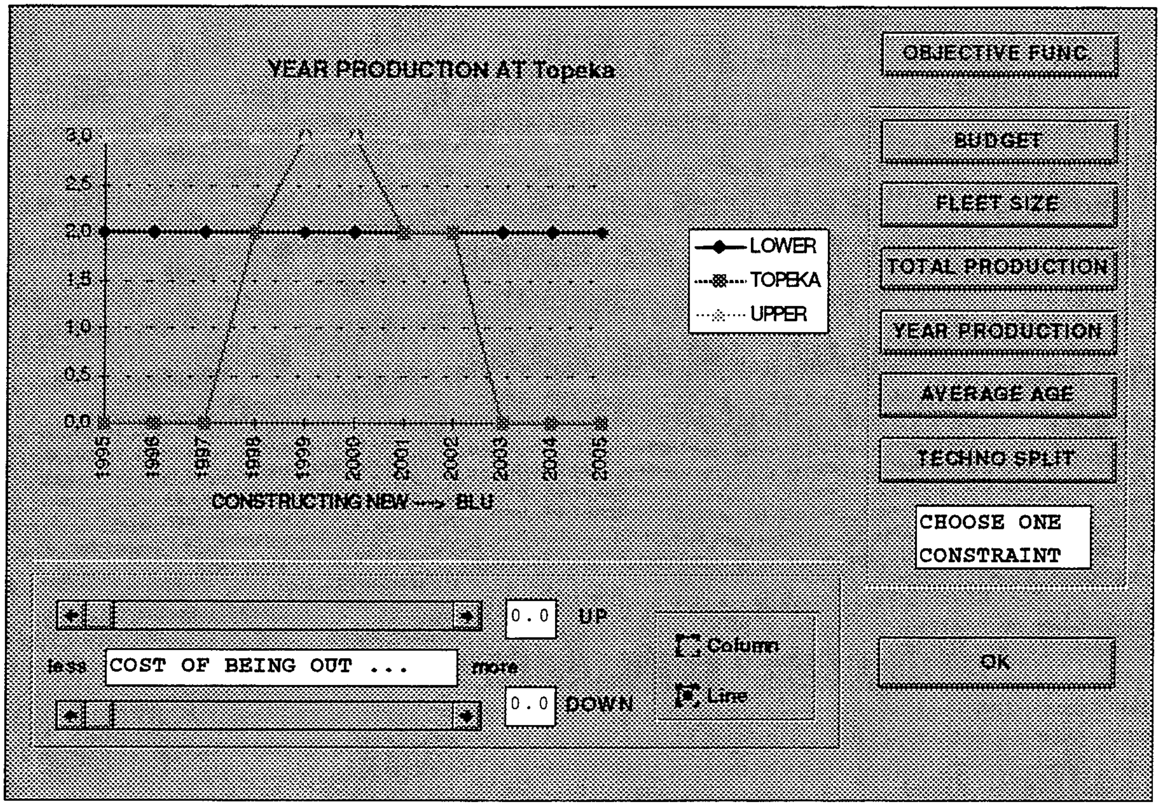

Figure 22 The YEAR PRODUCTION button shows the user the activity on the production lines. In this case Topeka is producing 12 new blu units between the years 1998 and 2002.

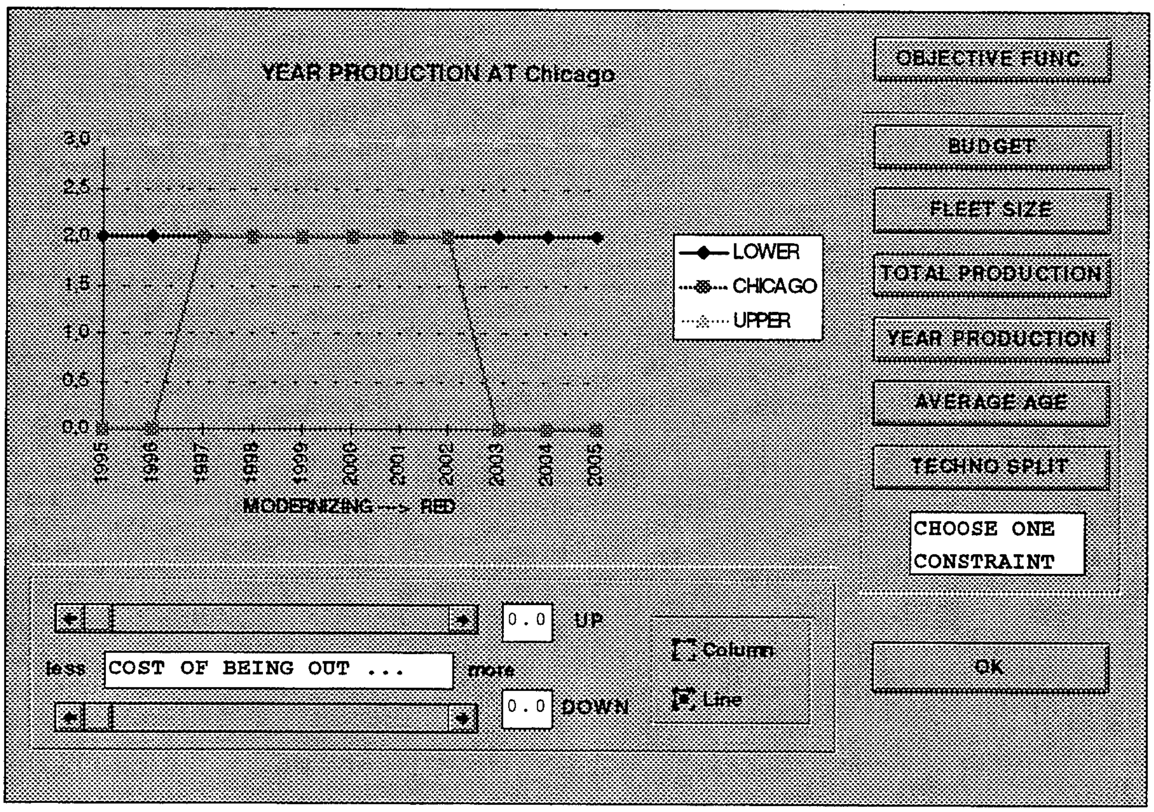

Figure 23 Clicking on the YEAR PRODUCTION button shows that Chicago is modernizing 12 red units between 1997 and 2003. Figures 27 and 28 show which cohorts contain these units.

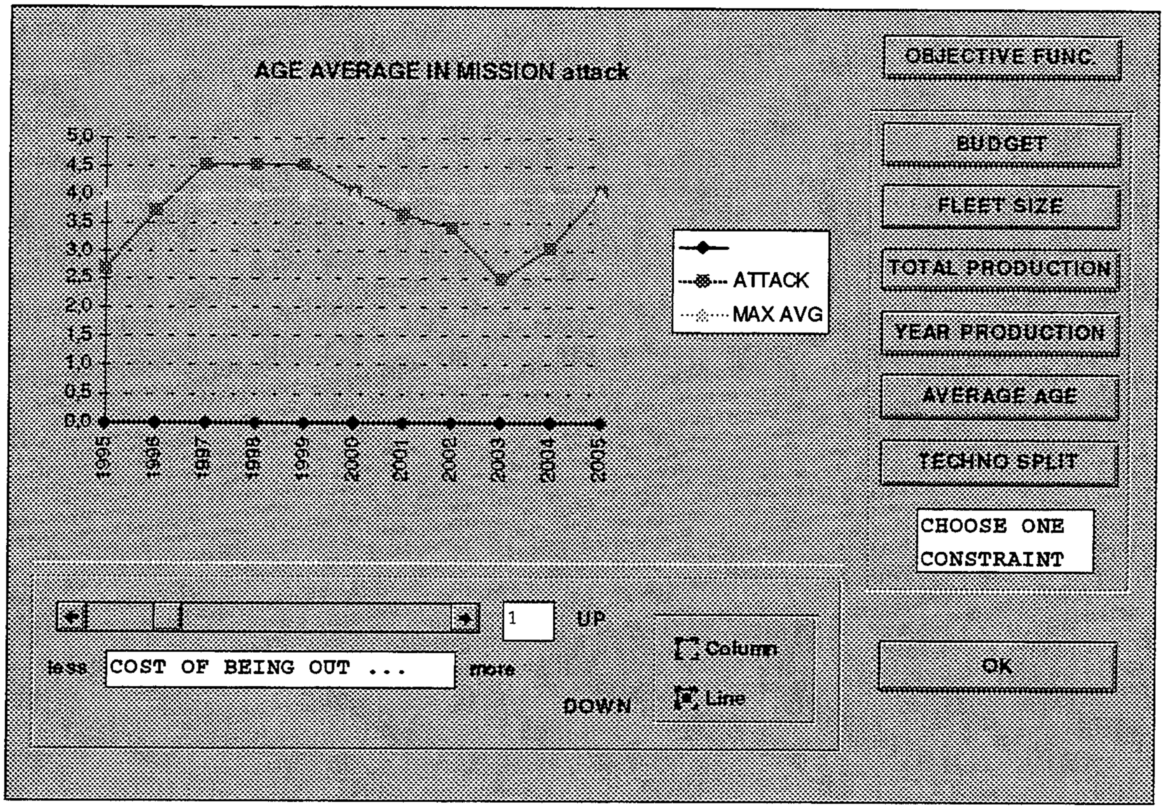

Figure 24 The AVERAGE AGE for mission attack have acceptable values. If we click on AVERAGE AGE again we can see that for mission scout we are also inside the limits. Notice that the value of the penalty weight associated with this constraint is set to the value 1.

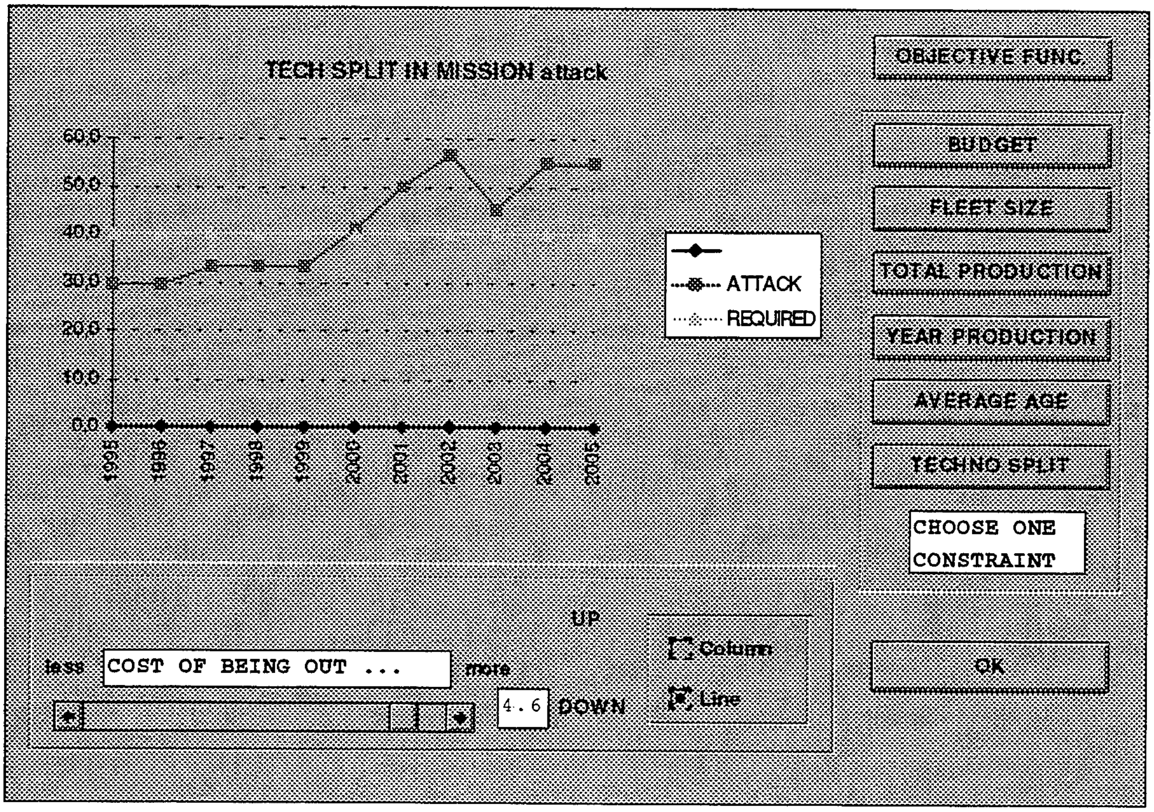

Figure 25 The TECHNO SPLIT value is not above desired limits until 1999. Again the decision maker must exercise judgment; he may decide that this solution is acceptable given the cost of this solution and the other constraint values.

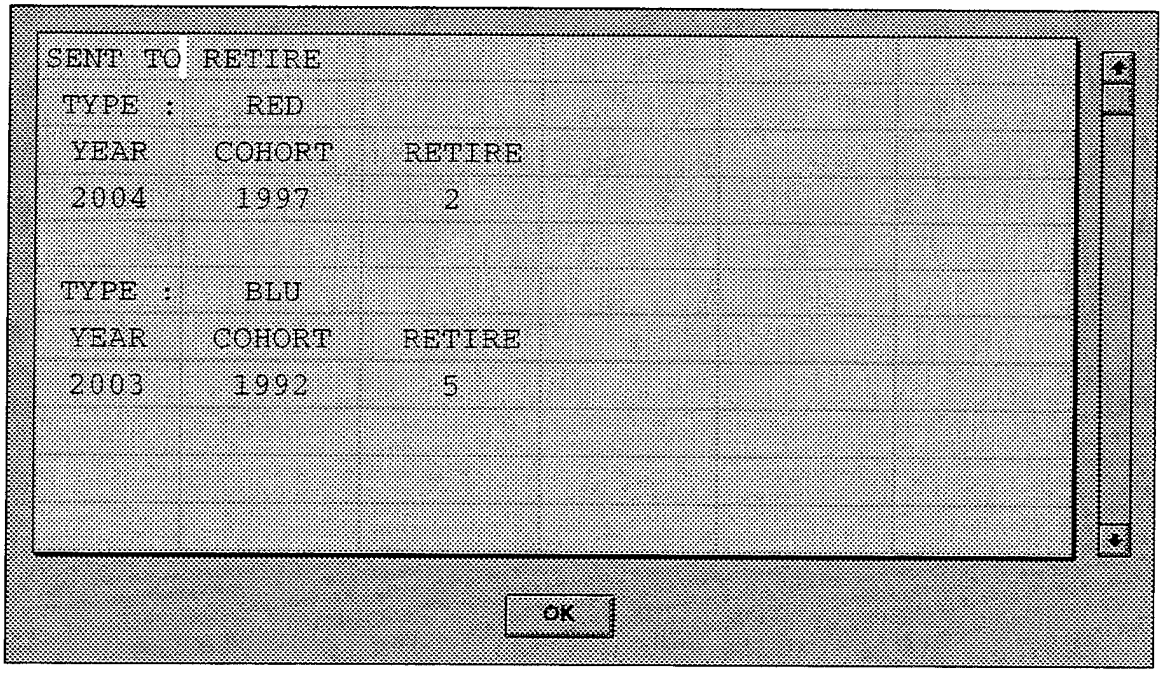

Figure 26 The user accesses this information through the View Retire item in the menu bar item Model in the Excel menu bar. Here the units retired are shown by year and by cohort.

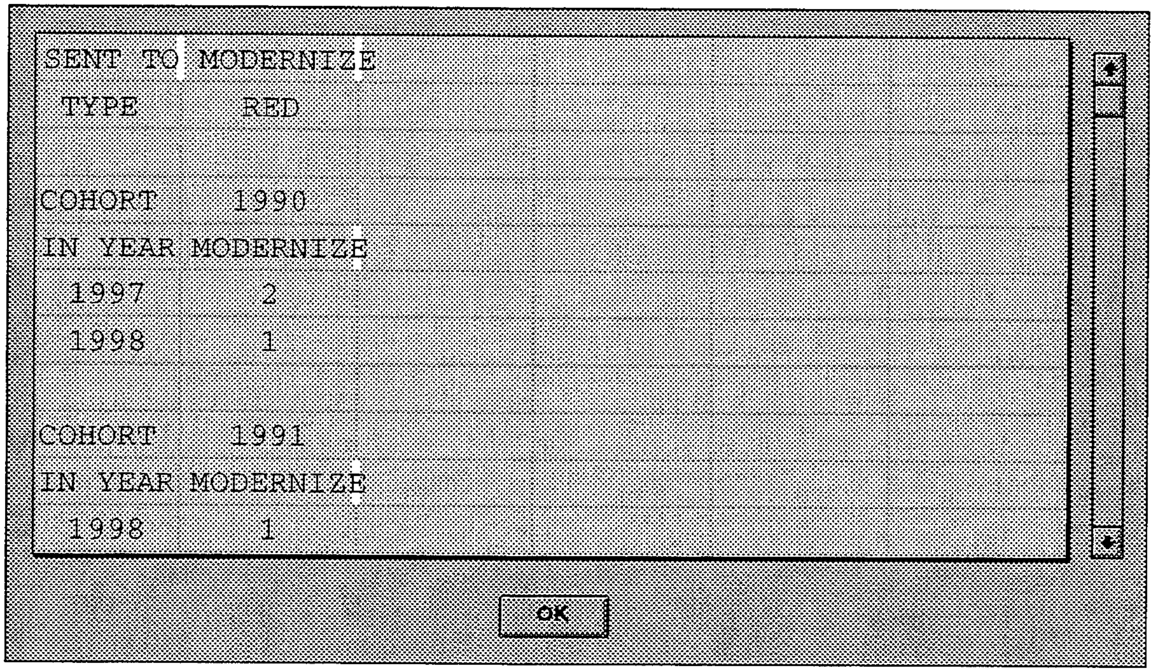

Figure 27 The user accesses this information through the View Modernize item in menu bar item Model in the Excel menu bar. It shows which units are sent to modernize from which cohort and what year. In our example we have three from the 1990 cohort and one from the 1991 cohort. In the next figure (the user will use the scroll bar to see it on screen) we can count 8 more making the 12 units that are the total modernized at Chicago (Fig. 23).

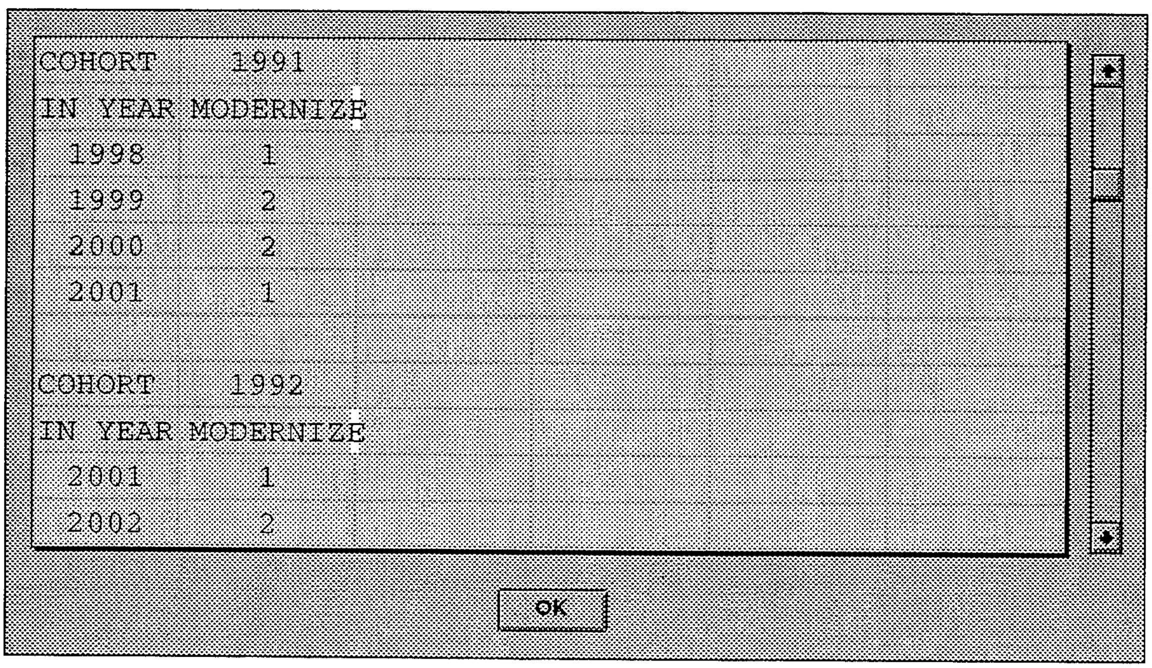

Figure 28 We have here one unit repeated from the last screen and the other 8 that complete the 12 units modernized at Chicago. The years in which the units are sent to be modernize are precisely the years of operation of the production facility.

APPENDIX C : INPUT CHECKLIST

This appendix present a list of the inputs that will be required by the model.

INITIAL PROBLEM SETTINGS

Planning horizon (years)
Missions to cover during the planning horizon
Assets that can accomplish the required missions
Production lines that can build or modernize those assets
Oldest cohort of the assets of each type

POLICY REQUIREMENTS

Maximum and minimum fleet size per mission
Minimum high technology proportion in each mission
Maximum average age of assets in each mission
Maximum and minimum year budget during planning horizon

INFORMATION ON THE ASSETS TO BUILD OR MODERNIZE

Maximum and minimum utilization life
Survival rate from one year to the next one (only when asset numbers are large enough for this to make sense)
Time, in years, that it takes to build the asset
Time, in years , that it takes to modernize the asset
Production cost of the asset
Modernization cost of the asset
Retiring cost of the asset
Years in which the asset is considered high technology (binary)
Initial inventory of assets at the beginning of the planning horizon
Missions that the asset can accomplish (binary)

INFORMATION ON THE PRODUCTION LINES

Maximum and minimum cumulative production on the line
Maximum and minimum yearly production on the line
Fixed cost of opening a line the year it is opened
Fixed yearly cost of keeping a line open
Number of years from the beginning of planning horizon before a line can be opened
Number of years from the beginning of planning horizon when the line must be closed
Assets that can be produced in each production line (binary)

OPERATION AND MAINTENANCE COST

For each asset during the planning horizon (Can be read from another Excel file)

LIST OF REFERENCES

Weingartner, Martin H., 1963, Mathematical Programming and the Analysis of Capital Budgeting Problems, Prentice Hall, Inc.

Hitch, Charles J., 1963, "The New Approach to Management in the US Defense Department," *Management Science* 9, pp. 1-8.

Brown, Gerald; Clemence, Robert; Teufert, William; and Wood Kevin , 1991, "An Optimization Model for Modernizing the Army's Helicopter Fleet," *Interfaces*, July-August, pp. 36-45.

Coblentz, Linda, 1991, "Linear Programming Analysis Tools for Acquisition Strategies: The Phoenix and Force Modernization Analyzer Models," Army Concepts Analysis Agency Working Papers.

Brooke, Anthony; Kendrick, David; and Meeraus, Alexander, 1993, GAMS release 2.25 A User's Guide, The Scientific Press.

Walkenbach, John, 1994, Excel 5 for Windows, Power Programming Techniques, IDG Books Worldwide, Inc.

Microsoft Excel User's Guide, 1994, Microsoft Corporation.

Office of Management and Budget (OMB), 1994, "Circular No. A-94, Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs".

Walker,Steven C., 1995, "Evaluating End Effects for Linear and Integer Programs Using Infinite-Horizon Linear Programming" , Naval Postgraduate School Ph.D. Dissertation.

Dundas, Joseph 1996, "Optimizing Replacement of the U.S. Navy's CH-46 D 'Sea Knight' Helicopter," Naval Postgraduate School Master's Thesis.

INITIAL DISTRIBUTION LIST

		No. Copies
1.	Defense Technical Information Center 8725 John J. Kingman Rd., STE 0944 Ft. Belvoir, VA 22060-6218	2
2.	Dudley Knox Library, Naval Postgraduate School 411 Dyer Rd. Monterey, CA 93943-5101	2
3.	Prof. Gordon H. Bradley Department of Operations Research Naval Postgraduate School Monterey, CA 93943-5002	6
4.	Prof. Gerald G. Brown Department of Operations Research Naval Postgraduate School Monterey, CA 93943-5002	2
5.	LCDR Gregorio Ameyugo GIMO Arturo Soria 287 28033 Madrid SPAIN	2
6.	CAPT. DIRECTOR GIMO Arturo Soria 287 28033 Madrid SPAIN	1
7.	JEFATURA DEL APOYO LOGISTICO DIRECCION DE APROVISIONAMIENTO Y TRANSPORTES Pio XII 82 28033 Madrid SPAIN	1
8.	MINISTERIO DE DEFENSA DIRECCION GENERAL DE ARMAMENTO Y MATERIAL Paseo de la Castellana Madrid SPAIN	1

9. ARGENTINE NAVAL COMMISSION 1
630 Indiana Avenue NW
Washington DC, 20004-2989