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Abstract: We studied two military radar system projects demand and estimated level of resources, including manpower in a variety of functions such as engineering analysis, design and drafting, and computer time. This report presents a Linear Programming model to minimize the cost of undertaking two projects simultaneously, subject to supply, demand and policy constraints.

A RESOURCE ALLOCATION PROBLEM

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EMP - P8905

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Submitted to Dr. Dundar Kocaoglu
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In Fulfillment Of The
EAS543 Operations Research in
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Linear Programming Term Project

EXECUTIVE SUMMARY

Data from two completed Hughes Aircraft Company projects (NOAH and BLOCK II) was used as a basis for estimating parameters for two future projects, Project 1 and Project 2. Projects 1 and 2 (both military radar systems) demand an estimated level of manpower in a variety of functions including engineering analysis, design, and drafting. The resources used for the project include computer time supplied by a Hughes CAD/CAE group and manpower (engineers, designers, and draftsmen) supplied by Division 1F.

The objective of the model is to minimize the cost of the resources necessary to undertake both projects simultaneously. The model is composed of a minimization objective, supply, demand, and policy constraints.

Sensitivity analyses are performed for at least one parameter in each of the vectors in the simplex tableau. The results of these manipulations are presented and discussed from a managerial viewpoint. Lindo was used to provide the optimal solutions and for postoptimal analyses.

EAS 543 Group Members working on the project include: Mark Chamberlain, Pandu Salam, Elizabeth Salgado, and Sida Zhou.

1.0 PROBLEM INTRODUCTION

The linear formulation problem described in this report represents two new future projects, Project 1 and Project 2, for Hughes Aircraft. The projects will be undertaken simultaneously. Data from two similar past projects, BLOCK II and NOAH, was used as a basis for estimating the future resources and constraints required to undertake the new projects. This is a reasonable assumption since radar system projects are often modifications of a previous design and are similar from project to project.

1.1 Minimization of Resource Costs

The objective of the linear model is to minimize the cost of combined resources used to undertake the projects. The resources used include computer time and manpower. The manpower resource can be divided into classification, function, and method.

Classification	Function	Methods
Engineer	Engineering	Computer
Designer	Designing	Manual
Draftsman	Drafting	

For example, an engineer may be required to do manual drafting, or a designer may be required to do engineering on the computer. Some constraints for task overlap apply and are discussed in section 1.5.

1.2 Computer Services Background

The Mechanical Integrated Product Systems (MIPS) staff works within Ground Systems Group (GSG) at Hughes Aircraft Company (HAC) to provide computer automated engineering services for several internal engineering divisions. These services include: planning and capital acquisitions, custom software development, vendor software support, hardware and network support, peripheral support, training in the use of computer-aided engineering (CAE) and computer-aided design (CAD) software, etcetera.

Division 1F's geographical plant area contains eight CAE/CAD engineering workstations. These engineering workstations represent the total computer resource used in the linear model formulation. MIPS assesses 1F a $10/hour computer connect fee for the use of any of these computers. The fee is calculated by multiplying $10 by the number of of connect hours used. The proceeds from the connect hour fee are used to offset the cost of services provided by MIPS. The fee is relatively constant over time.

1.3 Division 1F Operations and Projects

Some of Division 1F's business may include the engineering, design, drafting, and/or manufacturing of a wide variety of ground based radar systems. These systems are primarily developed under contract with the U.S. Department of Defense (DoD) and sold to various free world countries. Recent DoD contracts stipulate that Hughes' deliverable product contain the electronic CAD/CAE databases used to model and design the hardware system (since the DoD may not select Hughes as the manufacturer). Projects requiring electronic deliverables must be modeled using the CAD/CAE workstations instead of using older manual methods.

Raw data regarding two specific 1F radar system projects, BLOCK II and NOAH, was made available by a Division 1F manager for this EAS543 study, and may be viewed in Appendix D. Since the raw data could not be used in the exact form in which it was received, changes were made to make it compatible to the model formulation and yet reflect as accurate a measure of reality as possible.

BLOCK II data was more readily available than data on project NOAH. Where data for NOAH was insufficient, extrapolations from BLOCK II such as manpower ratios, etc., were used to approximate data for NOAH in accordance with the known data for NOAH.

1.4 Division 1F Personnel and Salaries

The 1F engineering group upon which the linear programming model is based was comprised of three engineers, four designers, and six draftsmen. These people constitute the total manpower resource used in the model. The "engineer", "designer", and "draftsman" title classifications represent the formal education, skill level, experience, and general salary range of the individual.

Salaries at Hughes Aircraft are treated as sensitive information and are confidential. However, Hughes supplied an average hourly burden rate range (salary plus overhead) per title classification. Employees and managers use this to calculate manpower costs or manpower savings. Although undocumented, it appears and seems logical that engineering personnel with CAE/CAD skills receive slightly higher salaries than their computer illiterate colleagues. This assumption was incorporated in the linear model in lieu of data supporting salary differentiation within title classifications.

For example, a manual hour was estimated to incur cost 1/3 above the bottom of the salary range and an hour of time spent by a computer literate employee was estimated to cost 1/3 below the top of the salary range. The engineer salary range is from $40-$60. The manual engineering tasks are estimated to cost $47/hr and the computer engineering manpower is estimated at $54/hr (excluding the $10/hour computer connect fee).

Since it is impossible to determine individual skills (i.e.; computer literacy) no attempt was made to do so. If actual skill and salary data had been supplied by Hughes a pairwise comparison method could have been used to more accurately determine the technical coefficients in the objective function as well as determine which individuals were in fact capable of using computer hours. As it now stands, the model formulation includes the assumption that all of the individuals within a classification have identical engineering and computer skills. In reality this is not the case. For any given project the skill levels and employee compensations may vary widely.

1.5 Task Overlap and Cross Training

All of the engineers have one or more degrees in mechanical engineering. Designers may or may not be degreed. Designers are usually promoted draftsman with many years of experience. Draftsman are highly skilled in drawing techniques and practices but lack the overall engineering education of the engineers and designers.

The mix of personnel that comprise the 13 member group is 23% engineers (3), 31% designers (4), 46% draftsman (6). This mix is not optimal because it would be very rare to undertake a project that required exactly 23% of the total manpower in engineering, 31% in designing, and 46% in drafting. In addition, the actual level of manpower fluctuates over time. In practice, this results in uneven workloads and some task overlap (see Appendix D, Hughes provided data on at least five tasks performed by cross-trained employees) by those that are cross trained.

Engineers may do the job of engineers, designers, and draftsman. Designers may do design tasks, drafting tasks, and limited engineering tasks. Draftsman may do drafting and limited designing. Draftsman cannot do engineering. Constraints were added to ensure that each function does the majority of tasks normal to their own classification (e.g. to ensure that engineers do most of the engineering, etc.). Each classification (engineer, designer, draftsman), based on their CAD/CAE productivity rate, performs their own function more economically than another would having a different classification. Task overlap occurs when the manpower resource of a given classification does not match the manpower requirement for that classification in the project, or when it is more economical to use cross-trained employees.

Since classifications were modeled, rather than actual individuals, no attempt was made to determine which individuals are cross trained for given functions. The model will determine the number of hours each classification will overlap. A subjective management decision, based on experience, is necessary to determine which person within each classification is most able to perform a given task of the job.

1.6 Productivity Contrasts

Estimates were used to factor productivity increases for CAE/CAD over older manual methods. An EAS543 report group participant (with years of relevant industrial experience) provided the estimates after considering past test and industry information. It is assumed that these estimates are as well founded as anything in print (printed estimates vary considerably) since actual productivity rates will vary from individual to individual and from project to project. Unpublished productivity rates measured by past benchmark studies at Hughes have varied according to the test participant, classification of the test participant, software familiarity, task familiarity, and system speed. A productivity factor measured on a given day, for a given person, on a given task, would vary according to the person, task and day. A factor that reflected the productivity increase of everyone in a given classification would be much less accurate. Despite the subjective nature of the productivity factors the concept of using a productivity factor in the model is undisputed. This actual factors used in our model are subjective and were based on actual tests, trends, and experience.

2.0 DATA SOURCES

Data for the model was supplied by Hughes Aircraft and is found in Appendix D. Data supplied by Hughes was converted from raw data into a usable format as described in following sections. Data necessary for the model but not supplied by Hughes is estimated and explained where used.

2.1 Productivity Rates

Productivity rates (as discussed in section 1.6) are listed below. For example, an engineer doing engineering and using the computer is twice as productive when compared using only manual methods (2/1=2), a designer doing engineering is twice as productive on the computer (1/0.5=2), a draftsman doing designing is three times more productive on a computer (1.5/0.5=3).

PRODUCTIVITY RATES			
Classification	Function	Computer	Manual
Engineer	Engineering	2	1
	Designing	3	1
	Drafting	5	1
Designer	Engineering	1	0.5
	Designing	3	1
	Drafting	5	1
Draftsman	Engineering	N/A	N/A
	Designing	1.5	0.5
	Drafting	5	1

2.2 Manpower Hours

The raw manpower data in Appendix D was supplied by Division 1F. The data was supplied in the form of hours per drawing. The following tables and figures summarize the data, and manipulations to the data, that was used in the model.

DATA WAS CONVERTED FROM HOURS/DRAWING						
RAW DATA Project:	Project 1 Block II		Project 2 NOAH			
Function	Hours	%%	Hours	%%	Total	%%
Eng/Tech Suprv	2205	28.0%	7068	36.2%	9273	33.9%
Layout/Design	3755	47.6%	4887	25.1%	8642	31.5%
Draft/Detail	1920	24.4%	7554	38.7%	9474	34.6%
Total	7880	100%	19509	100%	27389	100%

The raw data represents a mix of man hours and man-computer hours. Since the model requires manpower hours only, an equation was used to calculate the man hours from the man-computer mix. For example, the raw engineering hours (2205) for BLOCK II in the above table was converted to "refined data" hours (3550) using the following equation.

Example: Engineers raw data converted to refined data.
(2205 X .61 X 2) + ((1 - .61) X 2205) = 3550 hours

The number of terminals (8) divided by the number of people (13) to share the terminals equals 0.61. Under the assumption that the terminals are not otherwise allocated, each person can use a terminal 61% of the time. During the 61% of the time the person uses the terminal they will be saving a certain amount of time, as described by their productivity rate. In the example, 2 represents the engineers productivity factor (3 for the designers and 5 for the draftsman). The following table is a summary of the refined data.

REFINED DATA, CONVERTED FROM RAW DATA

REFINED DATA Project:	Project 1 Block II		Project 2 NOAH			
Function	Hours	%%	Hours	%%	Total	%%
Eng/Tech Suprv	3550	19.2%	11379	23.6%	14929	22.4%
Layout/Design	8336	45.1%	10849	22.5%	19185	28.7%
Draft/Detail	6604	35.7%	25985	53.9%	32589	48.9%
Total	18490	100%	48213	100%	66703	100%

2.3 Computer Hours

The total number of engineering CAE/CAD workstations in division 1F is eight. This represents 24,960 hours of computer time available during the 18 month estimated period of the projects. The computer time is calculated as follows:

#Stations X #Hrs/wk. X #Wks/mo. X #Month = Computer Hrs.
8 x 40 x 4.33333 x 18 = 24,960 hours

3.0 PROBLEM FORMULATION (THE MODEL)

The linear model formulation produced the following Lindo statistics: 28 row constraints; 32 decision variables; zero integer program variables; constraint nonzeroes number 174 of which 86 are -1; there are no single column constraints; four constraints are modeled with '<', 23 with '>', and none with '='; the objective is a minimization problem. The model is explained in detail in the remainder of section three. The Lindo model is included in full in Appendix A.

3.1 Decision Variables

The decision variables are defined in the following table.

DECISION VARIABLES AND DESCRIPTION

Var	Title	Project	Task	Method
A =>	Engineer	1	Engineering	Manual
B =>	Engineer	1	Designing	Manual
C =>	Engineer	1	Drafting	Manual
D =>	Engineer	1	Engineering	Computer
E =>	Engineer	1	Designing	Computer
F =>	Engineer	1	Drafting	Computer
G =>	Engineer	2	Engineering	Manual
H =>	Engineer	2	Designing	Manual
I =>	Engineer	2	Drafting	Manual
J =>	Engineer	2	Engineering	Computer
K =>	Engineer	2	Designing	Computer
L =>	Engineer	2	Drafting	Computer
M =>	Designer	1	Engineering	Manual
N =>	Designer	1	Designing	Manual
O =>	Designer	1	Drafting	Manual
P =>	Designer	1	Engineering	Computer
Q =>	Designer	1	Designing	Computer
R =>	Designer	1	Drafting	Computer
S =>	Designer	2	Engineering	Manual
T =>	Designer	2	Designing	Manual
U =>	Designer	2	Drafting	Manual
V =>	Designer	2	Engineering	Computer
W =>	Designer	2	Designing	Computer
X =>	Designer	2	Drafting	Computer
Y =>	Draftsman	1	Designing	Manual
Z =>	Draftsman	1	Drafting	Manual
AA=>	Draftsman	1	Designing	Computer
AB=>	Draftsman	1	Drafting	Computer
AC=>	Draftsman	2	Designing	Manual
AD=>	Draftsman	2	Drafting	Manual
AE=>	Draftsman	2	Designing	Computer
AF=>	Draftsman	2	Drafting	Computer

3.2 Objective Function

The goal of the objective function is to minimize the manpower costs necessary to complete Project 1 and Project 2. The technical coefficients used in the objective function are discussed in section 1.4. The objective function is:

```
MIN   47 A + 47 B + 47 C + 64 D + 64 E + 64 F + 47 G + 47
H + 47 I + 64 J + 64 K + 64 L + 43 M + 43 N + 43 O + 56 P
+ 56 Q + 56 R + 43 S + 43 T + 43 U + 56 V + 56 W + 56 X +
38 Y + 38 Z + 51 AA + 51 AB + 38 AC + 38 AD + 51 AE + 51AF
```

3.3 Constraint Listing

Lindo solved for the objective function according to the constraints listed below. A discussion of each constraint follows in sections 3.4, and 3.5. The objective function is numbered as constraint 1) so this listing begins with constraint 2).

```
2)      D + E + F + J + K + L + P + Q + R + V + W + X + AA
        +AB + AE + AF <=    24960
3)      J + K + L + V + W + X + AE + AF >=    17778
4)      A + 2 D + 0.5 M + P >=    3550
5)      B + 3 E + N + 3 Q + 0.5 Y + 1.5 AA >=    8336
6)      C + 5 F + O + 5 R + Z + 5 AB >=    6604
7)      G + 2 J + 0.5 S + V >=    11379
8)      H + 3 K + T + 3 W + 0.5 AC + 1.5 AE >=    10849
9)      I + 5 L + U + 5 X + AD + 5 AF >=    25985
10)     A + B + C + D + E + F + G + H + I + J + K + L
        <= 9360
11)     M + N + O + P + Q + R + S + T + U + V + W + X
        <=12480
12)     Y + Z + AA + AB + AC + AD + AE + AF <=    18720
13)     G + H + I + J + K + L >=    6667
14)     S + T + U + V + W + X >=    8889
15)     AC + AD + AE + AF >=    13334
16) - 0.7 I + 0.3 L - 0.7 U + 0.3 X - 0.7 AD + 0.3 AF
        >=    0
17)     0.6 A + 0.6 B + 0.6 C - 0.4 D - 0.4 E - 0.4 F >=    0
18)     0.7 M + 0.7 N + 0.7 O - 0.3 P - 0.3 Q - 0.3 R >=    0
19)     0.8 Y + 0.8 Z - 0.2 AA - 0.2 AB >=    0
20)     0.05 A + 0.05 D - 0.95 M - 0.95 P >=    0
21) - 0.88 B - 0.88 E + 0.12 N + 0.12 Q - 0.88 Y - 0.88 AA
        >=    0
22) - 0.61 C - 0.61 F - 0.61 O - 0.61 R + 0.39 Z +
        0.39 AB >=    0
23)     0.05 G + 0.05 J - 0.95 S - 0.95 V >=    0
24) - 0.88 H - 0.88 K + 0.12 T + 0.12 W - 0.88 AC - 0.88
        AE >=    0
25) - 0.61 I - 0.61 L - 0.61 U - 0.61 X + 0.39 AD + 0.39
        AF >=    0
```

```
26)    0.6 G + 0.6 H + 0.6 I - 0.4 J - 0.4 K - 0.4 L >=   0
27)    0.7 S + 0.7 T + 0.7 U - 0.3 V - 0.3 W - 0.3 X >=   0
28)    0.8 AC + 0.8 AD - 0.2 AE - 0.2 AF >=   0
END
```

3.4 Resource Constraints

The constraints which limit resources are discussed below.

Constraint 2) limits the total number of computer hours available to both projects to less than 24960 (as discussed in section 2.3).

Constraint 10) limits the the total number of engineer manpower hours used to less than 9360. This constraint is calculated: [(3 engineers) X (40 hours/week) X (4.333333 weeks/month) X (18 months) = 9360].

Constraint 11) limits the the total number of designer manpower hours used to less than 12480. This constraint is calculated: [(4 designers) X (40 hours/week) X (4.333333 weeks/month) X (18 months) = 12480].

Constraint 12) limits the the total number of draftsman manpower hours used to less than 18720. This constraint is calculated: [(6 draftsman) X (40 hours/week) X (4.333333 weeks/month) X (18 months) = 18720].

3.5 Demand Constraints

The constraints showing a demand for a given resource are described below.

Constraint 3) requires that Project 2 use at least 17778 computer hours. Since Project 2 is estimated to require 71% of the manpower it was allotted at least 71% of the computer hours. Since it is the larger of the two projects it will be guaranteed its share of the workstations.

Constraint 4) demands that at least 3550 hours of engineering are necessary for Project 1. This is based on the historical data supplied by Hughes as discussed in section 2.2.

Constraint 5) demands that at least 8336 hours of designing are necessary for Project 1. This is based on the historical data supplied by Hughes as discussed in section 2.2.

Constraint 6) demands that at least 6604 hours of drafting are necessary for Project 1. This is based on the historical data supplied by Hughes as discussed in section 2.2.

Constraint 7) demands that at least 11379 hours of engineering are necessary for Project 2. This is based on the historical data supplied by Hughes as discussed in section 2.2.

Constraint 8) demands that at least 10849 hours of engineering are necessary for Project 2. This is based on the historical data supplied by Hughes as discussed in section 2.2.

Constraint 9) demands that at least 25985 hours of engineering are necessary for Project 2. This is based on the historical data supplied by Hughes as discussed in section 2.2.

Constraint 13) ensures that at least 6667 engineer hours are spent on Project 2. Since Project 2 is estimated to require 71% of the manpower it was allotted at least 71% of the total engineer manpower hours. Since it is the larger of the two projects it will be guaranteed its share of engineer manpower.

Constraint 14) ensures that at least 8889 designer hours are spent on Project 2. Since Project 2 is estimated to require 71% of the manpower it was allotted at least 71% of the total designer manpower hours. Since it is the larger of the two projects it will be guaranteed its share of designer manpower.

Constraint 15) ensures that at least 13334 draftsman hours are spent on Project 2. Since Project 2 is estimated to require 71% of the manpower it was allotted at least 71% of the total draftsman manpower hours. Since it is the larger of the two projects it will be guaranteed its share of draftsman manpower.

Constraint 16) is a policy constraint. This constraint demands that 70% of the entire drafting function for Project 2 be done on a workstation. Since Project 2 is contracted by the Department of Defense the final product (e.g. the engineering drawings) must include CAD/CAE electronic databases.

Constraint 17) recognizes a large portion of an engineers daily schedule is spent in review meetings, contacting suppliers, communicating with peers and subordinates, and other non computer related tasks. This amount of time away from the computer is defined to be at least 40% of the workday. This constraint applies to Project 1 (see the explanation for constraint 26).

Constraint 18) recognizes a large portion of a designers daily schedule is spent in review meetings, contacting suppliers, communicating with others, and other non computer related tasks. This amount of time away from the computer is defined to be at least 30% of the workday. This constraint applies to Project 1 (see the explanation for constraint 27).

Constraint 19) recognizes that a portion of the draftsmen daily schedule is spent in meetings, contacting suppliers, communicating with others, and other non computer related tasks. This amount of time away from the computer is defined to be at least 20% of the workday. This constraint applies to Project 1 (see the explanation for constraint 28).

Constraint 20) represents the least amount of engineering required to be done by the engineers. This percentage (95%) was calculated using the Hughes data (sheet 1) in Appendix D and calculated as follows: [(117/2205) = 5% engineering done by a designer]. This applies to Project 1 (see the explanation for constraint 23).

Constraint 21) represents the least amount of designing required to be done by the designers. This percentage (61%) was calculated using the Hughes data (sheet 1) in Appendix D and calculated as follows: [((813 + 665)/3755) = 39% designing done by draftsmen]. This applies to Project 1 (see the explanation for constraint 24).

Constraint 22) represents the least amount of drafting required to be done by the draftsman. This percentage (88%) was calculated using the Hughes data (sheet 1) in Appendix D and calculated as follows: [((175+55)/1920) = 12% drafting done by a designer]. This applies to Project 1 (see the explanation for constraint 25).

Constraint 23) represents the least amount of engineering required to be done by the engineers. This percentage (95%) was calculated using the Hughes data (sheet 1) in Appendix D and calculated as follows: [(117/2205) = 5% engineering done by a designer]. This applies to Project 2 (see the explanation for constraint 20).

Constraint 24) represents the least amount of designing required to be done by the designers. This percentage (61%) was calculated using the Hughes data (sheet 1) in Appendix D and calculated as follows: [((813 + 665)/3755) = 39% designing done by draftsmen]. This applies to Project 2 (see the explanation for constraint 21).

Constraint 25) represents the least amount of drafting required to be done by the draftsman. This percentage (88%) was calculated using the Hughes data (sheet 1) in Appendix D and calculated as follows: [((175+55)/1920) = 12% drafting done by a designer]. This applies to Project 2 (see the explanation for constraint 22).

Constraint 26) recognizes a large portion of an engineers daily schedule is spent in review meetings, contacting suppliers, communicating with peers and subordinates, and other non computer related tasks. This amount of time away from the computer is defined to be at least 40% of the workday. This constraint applies to Project 2 (see the explanation for constraint 17).

Constraint 27) recognizes a large portion of a designers daily schedule is spent in review meetings, contacting suppliers, communicating with others, and other non computer related tasks. This amount of time away from the computer is defined to be at least 30% of the workday. This constraint applies to Project 2 (see the explanation for constraint 18).

Constraint 28) recognizes that a portion of the draftsmen daily schedule is spent in meetings, contacting suppliers, communicating with others, and other non computer related tasks. This amount of time away from the computer is defined to be at least 20% of the workday. This constraint applies to Project 2 (see the explanation for constraint 19).

4.0 SOLUTION

The solution for the linear program is listed in sections 4.1 through 4.5 and is composed of several parts: Objective Function Value, Decision Variable Values and Reduced Cost, Row Slack and Surplus Variables and Dual Prices, Objective Function Coefficient Ranges, Righthand Side Ranges.

4.1 Objective Function Value

```
LP OPTIMUM FOUND AT STEP      45

        OBJECTIVE FUNCTION VALUE

        1)      1844147.00
```

4.2 Decision Variable Values and Reduced Cost

VARIABLE	VALUE	REDUCED COST
A	887.500000	.000000
B	.000000	14.041670
C	.000000	24.226190
D	1331.250000	.000000
E	.000000	6.375000
F	.000000	13.880950
G	2754.153000	.000000
H	.000000	31.464970
I	.000000	31.464970
J	4131.229000	.000000
K	.000000	61.356690
L	.000000	61.356690
M	.000000	3.833336
N	1042.000000	.000000
O	.000000	10.184530
P	.000000	29.375000
Q	2431.333000	.000000
R	.000000	7.505951
S	.000000	14.945860
T	4029.544000	.000000
U	1879.885000	.000000
V	362.388500	.000000
W	1870.852000	.000000
X	746.330100	.000000
Y	.000000	.669641
Z	314.476200	.000000
AA	.000000	25.056550
AB	1257.905000	.000000
AC	.000000	.000000
AD	2666.800000	.000000
AE	804.599500	.000000
AF	9862.601000	.000000

4.3 Row Slack, Surplus Variables, Dual Prices

ROW	SLACK OR SURPLUS	DUAL PRICES
2)	2161.512000	.000000
3)	.000000	-13.000000
4)	.000000	-35.750000
5)	.000000	-21.708330
6)	.000000	-11.523810
7)	.000000	-29.891720
8)	.000000	.000000
9)	31606.340000	.000000
10)	255.867900	.000000
11)	117.666600	.000000
12)	3813.619000	.000000
13)	218.382100	.000000
14)	.000000	-43.000000
15)	.000000	-38.000000

16)	.000000	.000000
17)	.000000	-18.750000
18)	.000000	-30.416660
19)	.000000	-33.095240
20)	110.937500	.000000
21)	416.800000	.000000
22)	613.228600	.000000
23)	.000000	-31.464970
24)	.000000	.000000
25)	3284.475000	.000000
26)	.000000	-25.891720
27)	3242.729000	.000000
28)	.000000	.000000

NO. ITERATIONS= 45

4.4 Ranges In Which The Basis Is Unchanged

VARIABLE	CURRENT COEF	ALLOWABLE INCREASE	ALLOWABLE DECREASE
A	47.000000	18.722220	12.750000
B	47.000000	INFINITY	14.041670
C	47.000000	INFINITY	24.226190
D	64.000000	20.444460	37.444440
E	64.000000	INFINITY	6.375000
F	64.000000	INFINITY	13.880950
G	47.000000	42.222220	20.846150
H	47.000000	INFINITY	31.464970
I	47.000000	INFINITY	31.464970
J	64.000000	40.650000	82.333330
K	64.000000	INFINITY	61.356690
L	64.000000	INFINITY	61.356690
M	43.000000	INFINITY	3.833336
N	43.000000	4.380955	20.015870
O	43.000000	INFINITY	10.184530
P	56.000000	INFINITY	29.375000
Q	56.000000	4.591827	13.142870
R	56.000000	INFINITY	7.505951
S	43.000000	INFINITY	14.945860
T	43.000000	.000000	.000000
U	43.000000	.000000	.000000
V	56.000000	15.187700	813.000000
W	56.000000	.000000	.000000
X	56.000000	.000000	.000000
Y	38.000000	INFINITY	.669641
Z	38.000000	.703124	27.800000
AA	51.000000	INFINITY	25.056550
AB	51.000000	7.881248	3.515618
AC	38.000000	INFINITY	.000000
AD	38.000000	.000000	.000000
AE	51.000000	.000000	.000000
AF	51.000000	.000000	.000000

4.5 Righthand Side Ranges

ROW	CURRENT RHS	ALLOWABLE INCREASE	ALLOWABLE DECREASE
2	24960.000000	INFINITY	2161.512000
3	17778.000000	2161.512000	1428.321000
4	3550.000000	409.388600	3550.000000
5	8336.000000	282.399900	8336.000000
6	6604.000000	11347.940000	6604.000000
7	11379.000000	422.855300	360.905200
8	10849.000000	2856.643000	7160.848000
9	25985.000000	31606.340000	INFINITY
10	9360.000000	INFINITY	255.867900
11	12480.000000	INFINITY	117.666600
12	18720.000000	INFINITY	3813.619000
13	6667.000000	218.382100	INFINITY
14	8889.000000	117.666600	2232.955000
15	13334.000000	1602.372000	4053.412000
16	.000000	1479.909000	1563.069000
17	.000000	409.388600	710.000000
18	.000000	141.200000	833.600000
19	.000000	4004.300000	264.160000
20	.000000	110.937500	INFINITY
21	.000000	416.800000	INFINITY
22	.000000	613.228600	INFINITY
23	.000000	355.593800	342.860000
24	.000000	744.254600	3076.512000
25	.000000	3284.475000	INFINITY
26	.000000	422.855300	360.905200
27	.000000	3242.729000	INFINITY
28	.000000	1879.885000	746.330100

4.6 Allocation of Resources

The following table represents the final solution.

Project 1		Analysis	Design	Drafting
Engr.	Manual	887.5	-	-
	Comp.	1331.25	-	-
Design	Manual	-	1042.0	-
	Comp.	-	2431.33	-
Draft	Manual	-	-	314.476
	Comp.	-	-	1257.905

Project 2		Analysis	Design	Drafting
Engr.	Manual	2754.153	-	-
	Comp.	4131.229	-	-
Design	Manual	-	4029.544	1879.885
	Comp.	362.3805	1870.852	746.33
Draft	Manual	-	-	2666.80
	Comp.	-	804.995	9862.601

5.0 DISCUSSION AND ANALYSIS OF RESULTS

The Lindo solution to the linear programing model indicates that both Project 1 and Project 2 may be completed at a cost of $1,844,147 dollars.

5.1 Surplus Resource

The number of employees and the number of computers may be reduced since the results indicates surplus resource in these areas. The computer resource, engineer hours, designer hours and draftsman hours show slack and are not used at 100% capacity. Computer hour surplus is the result of constraints which allow portions of both projects' tasks to be done manually. The computer productivity rate increases allow the engineers, designers and draftsmen to do their tasks faster resulting in idle resources.

The manpower hours availability range within which manpower hours are allowed to decrease is too small. It is realistic to expect fluctuations in manpower that would exceed the allowable range. Promotions, resignations, transfers, retiring, etc. all have an impact on manpower availability.

5.2 Project 1 Observations

Interesting observations for Project 1 include:

1. Project 1 has no need for cross trained individuals since it can be completed without task overlap.

2. Project 1 can be finished using the minimum hours required for analysis, design and drafting (see section 3.5, constraints 4,5,6).

5.3 Project 2 Observations

Interesting observations for Project 2 are:

1. Project 2 requires cross trained individuals since there is some task overlap. The analysis can be finished using the minimum time required (see section 3.5, constraint 7).

2. Part of the analysis must be done by a designer(5% = 362.39/7247.77 see section 4.6). The designing may be finished using the minimum required resource (see section 3.5, constraint 8).

3. The draftsmen must do 12% of the designing (12% = 804.60/6704.99 see section 4.6, constraint 8).

4. To finish Project 2 we need to use more than the minimum engineer hours assigned to the project (surplus = 218.38 see section 4.2). The drafting task for Project 2 can not be finished using the hour assigned (surplus = 31606.34 see section 4.2). This is because part of the drafting should be done by hand and it takes more time to do the drafting by hand than when using the computer. The designers must do 18% of the drafting (2626.21/15155.61 see section 4.6).

5. With respect to manual hour estimates the engineers and drafters used the minimum percentage required (40% and 20% respectively) (surplus = 0 see section 4.2).

6. The designer should do 68% (5909/8889 see section 4.6) of his job by hand even when there is computer time available because manual hours are less expensive than computer hours. Using manual hours does not prohibit the project from being finished within the requirements. In addition, the designer is constrained to use not less than 30% manual time (meetings, etc.).

6.0 SENSITIVITY ANALYSIS

Sensitivity analysis provides insight into the post optimal solutions of a linear programming model. This insight cannot be gained through mere examination of the optimal solution. Sensitivity analysis involves "tweaking" (modifying) a variety of parameters in the model to represent either real world or "what if" fluctuations in resources, constraints, costs, etc. This tweaking may be done by discrete or continuous changes of the parameters. This approach is used for determining the impact that changes in the linear programming model has on the resulting problem solution. Sections 6.1 to 6.8 contain the sensitivity analyses performed on our model.

6.1 Sensitivity Analysis for Right-hand Side Values

B1, B2, (Row 2, Row 3)

These constraints represent the computer hours available for both projects. At least 17,778 hours for Project 2 must be satisfied. There is a slack variable associated with this constraint which means the resources are not fully used. By modifying the slack variable, a change in the Z value can be quantified. The following is a sample calculation to show how new Z values were found. The other constraints will be presented in a summary table.

Row 2: $-2161 < B2 < INFINITY$

$22799 < B2new < INFINITY$

and the new optimal value of Z is

$Znew = Zold + Z * deltaB2$

$= 1844147 + (0)\ (-2161)$

$= 1844147$

Row 3: $-1428 < B3 < 2161$

$16350 < B3new < 19939$

and the new optimal value of Z is

$Znew = Zold + Z * deltaB3$

$= 1844147 + (-13)\ (2161)$

$= 1873240$

and Z = 1844147 + (-13) (-1428)

= 1825583

1825583 < Znew < 1872240

Table 1

Row	Bi	Range of Bnew		Range of Znew	
		Higher	Lower	Higher	Lower
2	B2	22799	Infinity	Zold	Zold
3	B3	16350	19939	1825583	1872240
4	B4	0	3959	1717235	1858783
5	B5	0	8618	1663186	1850277
6	B6	0	17952	1768044	1974919
7	B7	11018	11802	1833359	1856787
8	B8	3689	13705	Zold	Zold
9	B9	-Infinity	57591	Zold	Zold
10	B10	9105	Infinity	Zold	Zold
11	B11	12363	Infinity	Zold	Zold
12	B12	14907	Infinity	Zold	Zold
13	B13	-Infinity	6885	Zold	Zold
14	B14	6657	9006	1748130	1849207
15	B15	9281	14936	1690117	1905037

6.2 Changes in Computer Hours (Bi)

Change in computer hours can be controlled easily by the manager, so it is wise to analyze this closely. As we can see from sensitivity analysis output, 2161 computer hours could be decreased without affecting the basic solution. A change in the total computer hours without becoming infeasible is possible by either adding or reducing the number of terminals or extending or reducing operation hours of the computers. Both of these methods are common practice. Extending computer hours could cause overtime to the workers which will cost more to the company, on the other hand, adding terminals will also cost a lot of money to buy computers and accessories. Therefore, the tradeoff between these choices should be considered. (The original solution was modeled with 8 terminals and is not included in Table 2.)

Table 2 data illustrates that adding a terminal will increase the cost. On the other hand, reducing the number of terminals will reduce the cost. Reducing the number of computer hours available by 6,240 hours (or by two terminals) results in a cost decrease of $49,540. The total computer hours for Project 2 may be reduced by its proportional allotment of the total computer hours of the original model. In practice, it is difficult if not impossible to schedule an even usage of the computer resource. Therefore a small surplus of computer hours is of benefit. The output files in Table 2 may be found in Appendix C.

Table 2

Number of Terminals	Total Comp.hour	Comp.hour Project 2	Z value $	Output File
5	15600	11111	Infeasible	outputC1
6	18720	13334	1794607	outputC2
7	21840	15556	1815261	outputC3
9	28080	20001	1873046	outputC4
10	31200	22223	1959040	outputC5
11	34320	24445	Infeasible	outputC6

6.3 Change in Number of Persons (Bi)

Manpower availability is a worthy point for analysis. Although only a small allowable margin for a decrease in manpower exists in this resource, it is worth trying to determine whether or not workers may be reduced.

The total number and mixture of engineers, designers and draftsmen were analyzed to reduce the number of personnel. Recall that the projects in the original data were modeled after a Division 1F group of 3 engineers, 4 designers, and 6 draftsmen. Table 3, illustrates that managers would face an infeasible condition if either one engineer or one designer is terminated and is not replaced. However, up to two draftsmen can be transferred or terminated. Reducing the number of draftsman by two would reduce costs by about $150,000. It is impossible to reduce three persons at a time in any combination.

Reducing personnel creates morale problems. The usual occurrence is to transfer the employee temporarily to another division that has more work (and more money), or to "eat the cost" until more work is available. Another alternative would be to take on an additional project to use up the surplus manpower. The output files in Table 3 may be found in Appendix C.

Table 3

Number of Engineer	Number of Designer	Number of Draftsmen	Z value	Output File
2	4	6	Infeasible	outputP1
3	3	6	Infeasible	outputP2
3	4	5	1759711	outputP3
3	4	4	1690118	outputP4
3	4	3	Infeasible	outputP5

6.4 Change in Both Computer Hours and Engineering Staff (Bi)

As can be seen from the previous sensitivity analyses (in section 6.1, 6.2, and 6.3), the cost can be reduced by reducing the computer hours or the number of persons. What would happen if we reduced both the number of people and the number of terminals simultaneously? An analysis determined that a reduction of two terminals and two draftsmen at the same time could reduce costs by $226,000. Appendix C contains the postoptimal analysis from which this conclusion was deduced.

6.5 Change in Productivity (Aij)

Productivity rate may easily fluctuate from time to time. Even one person can perform differently in a different time, condition and environment.
Productivity rates used in original problem are shown in Table 4 (see section 1.6 and 2.1 for an explanation of the rates).

Table 4

Task Title	Anal. Manual	Design Manual	Draft. manual	Anal. Comp.	Design Comp.	Drft. Comp.
Engineer	1	1	1	2	3	5
Designer	0.5	1	1	1	3	5
Draftsman	0	0.5	1	0	1.5	5

The productivity rate can be improved by training, experience, and CAE/CAD hardware and software performance enhancements. A 100% percent improvement in productivity was modeled (data shown in table 5) resulting in a $197,000 dollar decrease in cost. This may be an ambitious improvement rate, but it is not unrealistic especially when considering CAE/CAD system customization capabilities coupled with effective user training programs.

Table 5

Task Title	Anal. Manual	Design Manual	Draft. Manual	Anal. Comp.	Design Comp.	Draft. Comp.
Engineer	1	1	1	4	6	10
Designer	0.5	1	1	2	6	10
Draftman	0	0.5	1	0	3	10

6.6 Changes in Engineering Analysis, and Design Hours (Bi)

An increase in the number of engineering analysis and design hours over estimated amounts is not uncommon (even when cautious managers build a safety factor into their estimates they sometimes overrun). The increase usually happens because of error in a preliminary design or modifications in the actual design at any stage. Therefore, it is important for a project manager to know how flexible the available resource is to this increase.

The sensitivity analysis determined that any increase in engineering analysis and design hours could not be tolerated without extending the schedule of the project. The output files in Table 6 may be found in Appendix C.

Table 6

% Increase in Analysis	% Increase in Design	Z value	Output File
10	5	Infeasible	outputI1
5	2.5	Infeasible	outputI2

6.7 Changes in Policy (new constraint)

Over the years, as Hughes' CAE/CAD equipment and technology has been integrated, yearly goals have been set to achieve an increasing percentage of the total output in CAD. In recent years this forethought has prepared the company to compete on DoD contracts requiring the database's as deliverable products. The initial model required that 70% of the Project 2 drafting be done in CAD (see constraint 16). This policy will be changed, so it is worth analyzing the effect of the change. Table 7 illustrates the effect on cost when the percentage of work on the system increases and decreases. Changing the policy percentage up to 85% does not affect the final cost. CAE/CAD drawing will be used most of the time automatically because of higher productivity no matter what policy is in force. In addition, if the policy were increased to 90% the projects could not be undertaken with the available resources. The output files in Table 7 are found in Appendix C.

Table 7

% Drafting in CAD	Z value	Output File
90	Infeasible	outputL2
85	1844147	outputL4
80	1844147	outputL3
60	1844147	outputL5

6.8 Change in Cost Coefficient (Cj)

Salary's are discussed in section 1.4. All employees are paid according to the salary curve of their own classification. An engineer pinch hitting as a draftsman is not paid the draftsmen wage, nor is the designer paid the engineers wage when doing engineering. What would be the effect on cost if all of the staff were paid according to their function, rather than their classification? An analysis determined that costs would be reduced by $9,000 if employees salary was based on function. This means that the cost of an imperfectly allocated mixture of engineers, designers, and draftsmen on Projects 1 and 2 is $9,000. In practice, there is no reason to expect a variation in the salary ranges from that given in the objective function. Again, this conclusion was deduced from postoptimal analysis found in Appendix C.

7.0 CONCLUSIONS AND SUMMARY

Surplus computer, and manpower resource exists. Management should develop a plan to reduce, justify, or make effective use of this surplus.

The model (project) is highly sensitive to a reduction in the number of engineers or designers available. The number of engineers and the number of designers must be retained to make the model feasible. Reducing (reassignment, transfer, etc.) the number of draftsmen is allowable and will result in a decreased cost.

The engineering analysis and design hours needed to finish the projects cannot be increased beyond the maximum value allowed in the Lindo model due to limited resource.

The total cost of the project is very sensitive to the productivity of the manpower. Any increase or decrease in productivity rates has an impact in the total cost(increase or decrease) and in the decision variables. Therefore close attention should be given to the validity of those values.