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ENGINEERING & TECHNOLOGY MANAGEMENT

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Abstract: Consulting engineering is an industry where new technology can increase the quality of services to provide a better product. Computer aided design (CAD) is one of the latest advances to be used in projects. Although using CAD may increase productivity, it may dramatically increase costs. The challenge to project managers is how to allocate the limited hours of this new technology. This report presents a Linear Programming model to determine the optimal time distribution of the CAD stations among various disciplines of an engineering consultant firm in a multidisciplinary project to minimize the project cost for the client. The project uses personnel from different disciplines such as engineers, designers, drafters, secretaries and managers.

MINIMIZE ENGINEERING COST IN DESIGN PROJECTS USING COMPUTER AIDED DESIGN

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and S. Moss

EMP - P9009

Minimize Engineering Cost in Design Projects Using Computer Aided Design

Good project

EMGT: 543 Operations Research in Engineering Management

Professor: Dr. Dundar F. Kocaoglu, Spring 1990

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EXECUTIVE SUMMARY

The purpose of this project was to model a typical multi-discipline project of a heavy industrial engineering consultant firm. The project disciplines consist of project managers, engineers, designers, drafters, and secretaries.

The objective of the project was to minimize costs while maximizing production subject to limitations of the resources available. Each discipline was allotted a minimum portion of the total hours available for use. Each of the discipline's hours were divided among several tasks with a small amount of local slack remaining. A small percentage of the total hours were available to be used by any discipline (global slack). Also ingrained in the constraints was the tradeoff in productivity between time spent on the CAD (higher productivity at a higher cost) versus drafting board (lower productivity at a lower cost).

While there are many issues other than cost which affect the allocation of project hours (i.e. politics, capabilities of personnel, etc.), the results show that the project was very sensitive to those variables related to CAD. Specifically, the number of CAD stations available and the productivity ratio of CAD versus the drafting board were extremely critical. The ratio of CAD to drafting board productivity must be at least 1.5 to realize the savings. The cost of the project varied from under $78,000 with four CAD stations to over $86,000 with 1.2 CAD stations available for a given productivity ratio.

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INTRODUCTION

Today's marketplace is strongly influenced by service oriented products and corporations. In order to provide the quality of service, reach desired profit ranges, and maintain an edge on the competition, companies need to use all the available technologies in their industry.

Consulting engineering is one industry where new technology can increase the quality of services to provide a better product. The latest tool to be implemented is the computer aided design (CAD) stations. Consultants have seen increases in productivity and product quality with CAD. The challenge to project managers is how to allocate the limited hours of this new technology. Although CAD may increase productivity, it will dramatically increase the loss of overhead. It is vital that this resource be distributed in the most economical way.

The purpose of this project was to use a linear program, LINDO, to model a typical engineering project and determine the optimal distribution of hours among the various disciplines. Harris Group Inc., a multi-service engineering consulting firm which the project is based, consists of approximately 200 employees. A typical short schedule contract for this company is one month and budgeted at 2000 manhours. Harris Group presently has two CAD stations available for this project which will be utilized in the model. Using these constraints, the model was analyzed to minimize the project cost for the client.

PROBLEM FORMULATION

In order to formulate a model and quantify the variables, historical information was needed regarding Harris Group. Project managers and senior management were interviewed and data was gathered to formulate the model.

The necessary personnel requirements were identified for the project team and was composed of a project manager, design engineers, designers, drafters and a secretary. The minimum hour allocations for each of the project members was determined. Table 1 describes the task responsibilities of each of the disciplines.

Task Allocation (% of hours)

Discipline	CAD Station	Computer Station	Drafting Board	Desk Only	Out of Office	Variable Drafting	Local Slack	Min Total % of Job
Project Mgr	0	10	0	40	40	0	10	4
Engineer	1	15	9	35	25	5	10	20
Designer	10	15	5	20	15	25	10	42
Drafter	20	5	10	10	0	45	10	20
Secretary	0	40	0	50	0	0	10	4
Global Slack								10
Total								100

Table 1

Each project discipline was allotted a minimum percentage of the total project hours. The remaining 10 percent of hours (global slack) was distributed among the disciplines to obtain the minimum cost. Because their job responsibilities vary, each discipline has only a portion of their allotted hours assigned to a particular task. For example, the project manager will not spend any time on the CAD station nor the drafting board, however his responsibilities do include time out of the office (40%), desk work (40%), and some computer time (10%). Ten percent of the project managers time, local slack will be left over for the linear program to allocate.

The billing rates for each discipline at each task is summarized in Table 2. The billing rates for a person on CAD or computer station are the normal hourly rate plus $25/hr or $20/hr respectively. The out of office costs are $1/hr more to account for mileage, meals, and other expenses.

To formulate the linear equations, discipline variables were used to denote each project team member, such as:

PM - Project Manager
ER - Engineer
DE - Designer
DR - Drafter
SE - Secretary

Billing Rates

Discpline	CAD Station	Computer Station	Drafting Board	Desk Only	Out of Office	Base cost per hour
Project Manager		$90		$70	$71	$70
Engineer	$75	$70	$50	$50	$51	$50
Designer	$55	$50	$30	$30	$31	$30
Drafter	$52	$47	$27	$27	$27	$27
Secretary		$43		$23		$23

Table 2

Task variables were used to show the activities where time was being spent:

CAD - Computer aided design
CS - Computer station work
DB - Work on drafting board
DO - Work at desk
OUT - Out of office work
SA - Hours saved using CAD

Also, the status of some of the global and local variables was incorporated.

V - Variable quantity
F - Fixed quantity
S - Slack quantity

The discipline hour allocation and task work splits were generated with minimum requirements met in each category. For example, 35% for the engineer at the desk only was the absolute minimum requirement for the engineer to successfully complete his job. This is a fixed quantity (F). The engineers 5% variable drafting time could be allocated to CAD or the drafting board depending on what was available and what was most cost efficient. This is a variable quantity (V). The engineers 10% local slack allows the task distribution to vary up to 10%. This is a slack quantity (S).

The following is a description of the decision variables for the model.

P_SIZE = The total number of manhours needed to complete the project.

PM = Total hours allocated to the project manager.

PMCS = Project manager's hours at the computer station.

PMDO = Project manager's hours at his desk.

PMOUT = Project manager's hours out of the office.

ER = Total hours allocated to engineers.

ERCAD = Engineering hours on the CAD station.

ERCS = Engineering hours on the computer station.

ERDB = Engineering hours at the drafting board.

ERDO = Engineering hours at the desk.

EROUT = Engineering hours out of the office.

ERSA = Engineering hours saved using CAD instead of the drafting board.

ERCADF = Minimum engineering hours allotted to CAD.

ERCADV = Additional engineering hours allotted to CAD.

ERDBF = Minimum engineering hours allotted to the drafting board.

ERDBV = Additional engineering hours on the drafting board.

DE = Total hours for the designers.

DECAD = Designer hours allocated to CAD.

DECS = Designer hours at the computer station.

DEDB = Designer hours at the drafting board.

DEDO = Designer hours at the desk.

DEOUT = Designer hours out of the office.

DESA = Designer hours saved using CAD instead of drafting the board.

DECADF = Minimum CAD hours used by designers.

DECADV = Additional hours the designers spend on CAD.

DEDBF = Minimum drafting board hours used by designers.

DEDBV = Additional hours the designers spend on the drafting board.

DR = Total hours allotted to the draftsmen.

DRCAD = Drafters hours allotted to CAD.

DRCS = Drafters hours at the computer station.

DRDB = Drafters hours at the drafting board.

DRDO = Drafters hours at the desk.

DRSA = Drafters hours saved by using CAD instead of drafting the board.

DRCADF = Minimum drafting hours allotted to CAD.

DRCADV = Additional hours the drafters spend on CAD.

DRDBF = Minimum drafting hours allotted to the drafting board.

DRDBV = Additional hours the drafters spend on the drafting board.

SE = Total hours allotted to the secretary.

SECS = Secretary's hours at the computer station.

SEDO = Secretary's hours at the desk.

CAD = Total CAD hours for the project.

NUM_CAD = Number of CAD stations available.

NUM_PM = Number of project managers required.

NUM_ER = Number of engineers required.

NUM_DE = Number of designers required.

NUM_DR = Number of drafters required.

NUM_SE = Number of secretaries required.

NUM_CS = Number of computer stations required.

Objective Function

The purpose of the model was to use the linear programming tool LINDO, to minimize the cost of completing a typical project of 2000 manhours. Using the above decision variables the following objective function was developed.

```
MIN Z =          + 90 PMCS            + 70 PMDO + 71 PMOUT
    + 75 ERCAD + 70 ERCS + 50 ERDB + 50 ERDO + 51 EROUT
    + 55 DECAD + 50 DECS + 30 DEDB + 30 DEDO + 31 DEOUT
    + 52 DRCAD + 47 DRCS + 27 DRDB + 27 DRDO
               + 43 SECS           + 23 SEDO
```

Subject to the following constraints

The Project Size

A typical project comprised of a 2000 manhour limit and a one month time frame was analyzed.

```
2)  P_SIZE = 2000                        ! DEFINE TOTAL ESTIMATED PROJECT SIZE
3)  PM + ER + DE + DR + SE - P_SIZE = 0  ! TOTAL TIME USED BY ALL DISCIPLINES
```

The Project Manager

From the information collected, a project manager was found to have a minimum of 4% of the total project hours.

```
4)  PM - .04 P_SIZE >= 0                 ! REQUIRES 4% OF TOTAL HOURS
```

A minimum of 10% of the project managers time will be spent on the computer station, a minimum of 40% will be spent at the desk doing project work, and finally, 40% will be spent outside the office communicating project status with the client. Recall, 10% of the project managers time will be local slack. These categories sum to equal the total required hours spent by the project manager. This allows some flexibility in the distribution of the project managers hours.

```
5)  PMCS + PMDO + PMOUT - PM = 0         ! TOTAL PM HOURS
6)  PMCS - .10 PM >= 0                   ! @ COMPUTER
7)  PMDO - .40 PM >= 0                   ! @ DESK
8)  PMOUT - .40 PM >= 0                  ! OUT OF OFFICE
```

Engineers

The data gathered indicated that the total engineering hours are equal to at least 20% of the total project size.

```
9)  ER - .20 P_SIZE >= 0                          ! REQUIRES 20% OF TOTAL HOURS
```

From past project history, it was determined a minimum of 35% of the engineers time was spent at the desk, a minimum of 25% of the time was spent out of the office, and 15% of the time was spent at the computer station. At least 1% of his time was allotted to CAD, and a minimum of 9% of the time was spent at the drafting board. The sum of these variables will equal the total needed by the engineers.

```
10) ERCAD + ERCS + ERDB + ERDO + EROUT + ERSA - ER = 0        ! TOTAL ER HOURS
11) ERDO - .35 ER >= 0                            ! @ DESK
12) EROUT - .25 ER >= 0                           ! OUT OF OFFICE
13) ERCS - .15 ER >= 0                            ! @ COMPUTER
14) ERDBF - .09 ER >= 0                           ! MIN DRAFTING BOARD HOURS
15) ERCADF - .01 ER >= 0                          ! MIN CAD TIME
```

In the consulting firm investigated, there has been a trend that when using CAD stations the productivity has doubled in comparison to doing the same work on the drafting board. According to the executive vice president in charge of computer resources, a CAD system will not even be considered for purchase unless a 2 to 1 productivity ratio can be insured. The 2 to 1 productivity applies to personnel who have experience on CAD and are beyond the learning curve. A large portion of the work done in heavy industrial consulting lends itself to CAD because of the repetition involved.

The productivity factor was modeled by equating an hour of CAD used to an hour saved (denoted as ERSA). The engineering hour saved was billed out at $0/hr, therefore that became a free hour. For example, if there were 20 variable hours, LINDO will either allocate these to CAD or the drafting board, depending on what was available. If the hours were allocated to CAD, the project would be billed for 10 hours at the engineers CAD billing rate ($75/hr). If the hours were allocated to the drafting board, the project would be charged for 20 hours at the engineers drafting board billing rate ($50/hr).

```
16) ERCADV - ERSA = 0                             ! FOR EVERY CAD HOUR 1 HOUR IS SAVED
17) ERCADV + ERDBV + ERSA - .05 ER >= 0 ! @ BOARD OR/AND HOUR CAD + SAVED
18) ERCADV + ERCADF - ERCAD = 0                   ! TOTAL CAD HOURS
19) ERDBF + ERDBV - ERDB = 0                      ! TOTAL DRAFTING BOARD HOURS
```

Designers

The designers were given a minimum of 42% of the total hours. Designers generally require the majority of the project time. The designers were required to spend a minimum of 20% of their time at their desk, 15% out of the office, 15% at the computer station, 10% at the CAD station, and 5% at the drafting board. The designers have 25% variable time in which there was freedom to work on CAD or the drafting board. The designers also had a 10% local slack time. Again, it was assumed the designer was twice as fast on the CAD station as at the drafting board (i.e. for every CAD hour worked 1 hour was saved). The variable CAD hours plus the variable hours on the drafting board plus hours saved must be greater than 25% of the designer's total hours.

```
20) DE - .42 P_SIZE >= 0                        ! REQUIRES 42% OF TOTAL HOURS
21) DECAD + DECS + DEDB + DEDO + DEOUT + DESA - DE = 0      ! TOTAL DE HOURS
22) DEDO - .20 DE >= 0                          ! @ DESK
23) DEOUT - .15 DE >= 0                         ! OUT OF OFFICE
24) DECS - .15 DE >= 0                          ! @ COMPUTER
25) DEDBF - .05 DE >= 0                         ! MIN DRAFTING BOARD HOURS
26) DECADF - .10 DE >= 0                        ! MIN CAD TIME
27) DECADV - DESA = 0                           ! FOR EVERY CAD HOUR 1 HOUR IS SAVED
28) DECADV + DEDBV + DESA - .25 DE >= 0         ! @ BOARD OR/AND HOUR CAD + SAVED
29) DECADV + DECADF - DECAD = 0                 ! TOTAL CAD HOURS
30) DEDBF + DEDBV - DEDB = 0                    ! TOTAL DRAFTING BOARD HOURS
```

Drafters

The drafters were assigned 20% of the total job since their abilities are somewhat limited as compared to the designers. As with the designers discussed above, the drafter's time was allotted 10% at the desk, 5% at the computer, 5% at the drafting board, 20% CAD, 45% variable drafting, and 10% local slack. The variable hours on CAD and the drafting board plus the hours saved must be greater than 45% of the time allotted to the draftsmen.

```
31) DR - .20 P_SIZE >= 0                        ! REQUIRES 20% OF TOTAL HOURS
32) DRCAD + DRCS + DRDB + DRDO + DRSA - DR = 0          ! TOTAL DR HOURS
33) DRDO - .10 DR >= 0                          ! @ DESK
34) DRCS - .05 DR >= 0                          ! @ COMPUTER
35) DRDBF - .10 DR >= 0                         ! MIN DRAFTING BOARD HOURS
36) DRCADF - .20 DR >= 0                        ! MIN CAD BOARD HOURS
37) DRCADV - DRSA = 0                           ! FOR EVERY CAD HOUR 1 HOUR IS SAVED
38) DRCADV + DRDBV + DRSA - .45 DR >= 0         ! @ BOARD OR/AND HOUR CAD + SAVED
39) DRCADV + DRCADF - DRCAD = 0                 ! TOTAL CAD HOURS
40) DRDBF + DRDBV - DRDB = 0                    ! TOTAL DRAFTING BOARD HOURS
```

Secretary

The secretary was allowed to charge 4% of her time to the job. The secretary's time was split between the computer station (at least 40%) and the desk (at least 50%). The remaining 10% was local slack time.

```
41) SE - .04 P_SIZE = 0                         ! REQUIRES 4% OF TOTAL HOURS
42) SECS + SEDO - SE = 0                        ! TOTAL SE HOURS
```

```
43) SECS - .4 SE >= 0                          ! @ COMPUTER
44) SEDO - .50 SE >= 0                         ! @ DESK
```

The following is the complete LINDO model used:

```
!              Minimize Engineering Cost in Design Projects
!                    Using Computer Aided Design
!
!***********************   OBJECTIVE FUNCTION  ****************************
MIN              90 PMCS              + 70 PMDO + 71 PMOUT
   + 75 ERCAD + 70 ERCS + 50 ERDB + 50 ERDO + 51 EROUT
   + 55 DECAD + 50 DECS + 30 DEDB + 30 DEDO + 31 DEOUT
   + 52 DRCAD + 47 DRCS + 27 DRDB + 27 DRDO
             + 43 SECS              + 23 SEDO
!
SUBJECT TO
!***********************  PROJECT SIZE CONSTRAINTS   ***********************
2)  P_SIZE = 2000                           ! DEFINE TOTAL ESTIMATED PROJECT SIZE
3)  PM + ER + DE + DR + SE - P_SIZE = 0 ! TOTAL TIME USED BY ALL
!
!*******************    PROJECT MANAGER'S CONSTRAINTS   ********************
4)  PM - .04 P_SIZE >= 0                    ! REQUIRES 4% OF TOTAL HOURS
5)  PMCS + PMDO + PMOUT - PM = 0            ! TOTAL PM HOURS
6)  PMCS - .10 PM >= 0                      ! @ COMPUTER
7)  PMDO - .40 PM >= 0                      ! @ DESK
8)  PMOUT - .40 PM >= 0                     ! OUT OF OFFICE
!
!******************    ENGINEER'S CONSTRAINTS  *****************************
9)  ER - .20 P_SIZE >= 0                    ! REQUIRES 20% OF TOTAL HOURS
10) ERCAD + ERCS + ERDB + ERDO + EROUT + ERSA - ER = 0       ! TOTAL ER HOURS
11) ERDO - .35 ER >= 0                      ! @ DESK
12) EROUT - .25 ER >= 0                     ! OUT OF OFFICE
13) ERCS - .15 ER >= 0                      ! @ COMPUTER
14) ERDBF - .09 ER >= 0                     ! MIN DRAFTING BOARD HOURS
15) ERCADF - .01 ER >= 0                    ! MIN CAD TIME
16) ERCADV - ERSA = 0                       ! FOR EVERY CAD HOUR 1 HOUR IS SAVED
17) ERCADV + ERDBV + ERSA - .05 ER >= 0 ! @ BOARD OR/AND HOUR CAD + SAVED
18) ERCADV + ERCADF - ERCAD = 0             ! TOTAL CAD HOURS
19) ERDBF + ERDBV - ERDB = 0                ! TOTAL DRAFTING BOARD HOURS
!
!******************    DESIGNER'S CONSTRAINTS  ****************************
20) DE - .42 P_SIZE >= 0                    ! REQUIRES 42% OF TOTAL HOURS
21) DECAD + DECS + DEDB + DEDO + DEOUT + DESA - DE = 0       ! TOTAL DE HOURS
22) DEDO - .20 DE >= 0                      ! @ DESK
23) DEOUT - .15 DE >= 0                     ! OUT OF OFFICE
24) DECS - .15 DE >= 0                      ! @ COMPUTER
25) DEDBF - .05 DE >= 0                     ! MIN DRAFTING BOARD HOURS
26) DECADF - .10 DE >= 0                    ! MIN CAD TIME
27) DECADV - DESA = 0                       ! FOR EVERY CAD HOUR 1 HOUR IS SAVED
28) DECADV + DEDBV + DESA - .25 DE >= 0 ! @ BOARD OR/AND HOUR CAD + SAVED
29) DECADV + DECADF - DECAD = 0             ! TOTAL CAD HOURS
```

```
30) DEDBF + DEDBV - DEDB = 0              ! TOTAL DRAFTING BOARD HOURS
!
!*******************    DRAFTER'S CONSTRAINTS    ****************************
31) DR - .20 P_SIZE >= 0                  ! REQUIRES 20% OF TOTAL HOURS
32) DRCAD + DRCS + DRDB + DRDO + DRSA - DR = 0        ! TOTAL DR HOURS
33) DRDO - .10 DR >= 0                    ! @ DESK
34) DRCS - .05 DR >= 0                    ! @ COMPUTER
35) DRDBF - .10 DR >= 0                   ! MIN DRAFTING BOARD HOURS
36) DRCADF - .20 DR >= 0                  ! MIN CAD HOURS
37) DRCADV - DRSA = 0                     ! FOR EVERY CAD HOUR 1 HOUR IS SAVED
38) DRCADV + DRDBV + DRSA - .45 DR >= 0 ! @ BOARD OR/AND HOUR CAD + SAVED
39) DRCADV + DRCADF - DRCAD = 0           ! TOTAL CAD HOURS
40) DRDBF + DRDBV - DRDB = 0              ! TOTAL DRAFTING BOARD HOURS
!
!*******************    SECRETARY'S CONSTRAINTS    ************************
41) SE - .04 P_SIZE = 0                   ! REQUIRES 4% OF TOTAL HOURS
42) SECS + SEDO - SE = 0                  ! TOTAL SE HOURS
43) SECS - .4 SE >= 0                     ! @ COMPUTER
44) SEDO - .50 SE >= 0                    ! @ DESK
!
!***********************    CAD CONSTRAINTS    ***************************
45) ERCAD + DECAD + DRCAD - CAD = 0       ! TOTAL # OF CAD HOURS WORKED
46) .00694 CAD - NUM_CAD = 0              ! # OF CAD STATIONS REQUIRED
47) NUM_CAD <= 2                          ! SET THE # OF CAD'S AVAILABLE
!
!***********************    FOR INFORMATION    ***************************
!
!    THE NUMBER OF PEOPLE, CAD STATIONS AND COMPUTER STATIONS ARE
!    BASED ON A ONE MONTH WORK SCHEDULE OR 160 HOURS.  AVAILABILITY
!    OF EQUIPMENT IS 90% .9 (160) = 144, THEREFORE 1/160 = .00625 AND 1/144 =
     .00694
!
48) PMCS + ERCS + DECS + DRCS + SECS - CS = 0 ! # OF COMPUTER STATION HOURS
49) ERDB + DEDB + DRDB - DB = 0            ! TOTAL # OF DRAFTING BOARD HOURS
50) PMDO + ERDO + DEDO + DRDO + SEDO - DO = 0 ! TOTAL # OF DESK HOURS
51) PMOUT + EROUT + DEOUT - OUT = 0        ! TOTAL # OF OUT OF OFFICE HOURS
52) ERSA + DESA + DRSA - SAVE_HR = 0       ! TOTAL # OF SAVED HOURS
53) 75 ERSA + 55 DESA + 52 DRSA - SAVE_$ = 0  ! AMOUNT OF MONEY SAVED
54) .00625 PM - NUM_PM = 0                 ! THE # OF PROJECT MANGERS REQUIRED
55) .00625 ER - .00625 ERSA - NUM_ER = 0       ! THE # OF ENGINEERS REQUIRED
56) .00625 DE - .00625 DESA - NUM_DE = 0       ! THE # OF DESIGNERS REQUIRED
57) .00625 DR - .00625 DRSA - NUM_DR = 0       ! THE # OF DRAFTERS REQUIRED
58) .00625 SE - NUM_SE = 0                     ! THE # OF SECRETARIES REQUIRED
59) .00694 CS - NUM_CS = 0                     ! THE # OF COMPUTER REQUIRED
!
END
LEAVE
```

SOLUTION

The base LINDO model, as listed above, with 2000 hours of consulting time, two CAD stations, and a 2 to 1 CAD productivity ratio, cost $78,417. The total number of hours worked by each discipline is summarized in Table 3. The total number of hours worked at each station and the number of required personnel for each discipline can be read from the LINDO solution in the appendix.

SENSITIVITY ANALYSIS

Reduced Costs and Objective Function Coefficients

The billing rate for an engineer on CAD or the drafting board is constant regardless if it was a fixed or variable hour. From the appendix, the reduced costs are summarized below. Note all other variables had a zero reduced cost.

Variable	Value	Reduced Costs
ERDBV	.0	10
DRCADV	.0	3

Engineers equation for billable dollars:

($75/hr)ERCAD+($70/hr)ERCS+($50/hr)ERDB+($50/hr)ERDO+($51/hr)EROUT

+($0/hr)ERSA

Designers equation for billable dollars:

($55/hr)DECAD+($50/hr)DECS+($30/hr)DEDB+($30/hr)DEDO+($31/hr)DEOUT

Drafters equation for billable dollars:

($52/hr)DRCAD+($47/hr)DRCS+($27/hr)DRDB+($27/hr)DRDO

The productivity of a person on CAD is two times greater than that of an individual on the drafting board. If the engineer on the drafting board was billed out at $50/hr for one hour of work, it would cost the client $50. The engineer on CAD was twice as productive, therefore it only takes a 1/2 hour on CAD to do one hour of work on the board. If the engineer has a $75/hr billing rate, it will cost $37.50 for the equivalent of one hour of work. The CAD was therefore more cost efficient when compared to the drafting board ($37.50/hr vs $50/hr). Since the linear program

TASKS

	CAD	CS	DB	DO	OUT	SA	
PM		$90/hr PMCS F 8		+ $70/hr PMDO F | S + 40	+ $71/hr PMOUT F + 32		= PM = 80 hrs
ER	$75/hr ERCAD F | V | S 4 + 30	+ $70/hr ERCS F + 60	+ $50/hr ERDB F | V + 36 + 0	+ $50/hr ERDO F + 140	+ $51/hr EROUT F + 100	+ $0/hr ERSA V | S + 30	= ER = 400 hrs
	(30)			EQUAL		(30)	
DE	$55/hr DECAD F V 84 + 50.1	+ $50/hr DECS F + 126	+ $30/hr DEDB F V | S + 42 + 193.6	+ $30/hr DEDO F + 168	+ $31/hr DEOUT F + 126	+ $0/hr DESA F + 50.1	= DE = 840 hrs
	(50.1)			EQUAL		(50.1)	
DR	$52/hr DRCAD F V 120 + 0	+ $47/hr DRCS F + 30	+ $27/hr DRDB F V + 60 + 270	+ $27/hr DRDO F | S + 120	+	+ $0/hr DRSA F + 0	= DR = 600 hrs
	(0)			EQUAL		(0)	
SE		$42/hr SECS F 32		+ $23/hr SEDO F | S + 148			= SE = 80 hrs
	Sum = 288	Sum = + 256	Sum = + 601.6	Sum = + 516	Sum = + 258	Sum = + 80.1	= 2000 hrs

Table 3

seeks to minimize costs, the competing CAD hours were allocated to the discipline with the highest billing rate first. The billing rates for the engineer were greater than those of the designer which were greater than that of the drafters. This means with the given resources, the engineer will had first access to extra CAD hours. Any CAD hours not used by the engineer were then given to the designer. The designer then used any available CAD hours and if there were extra, they were given to the drafters. The drafter was the last discipline to receive any of the limited CAD hours, since the drafters CAD billing rate was the least.
Recall CAD and drafting board hours are composed of both fixed and variable quantities. For example,

18) ERCADV + ERCADF - ERCAD = 0 ! TOTAL CAD HOURS
19) ERDBF + ERDBV - ERDB = 0 ! TOTAL DRAFTING BOARD HRS

The linear program produced the following results.

- Engineer
  - ERCAD =
    - ERCADF = 4 hours
    - ERCADV = 30 hours - Max CAD
  - ERDB =
    - ERDBF = 36 hours
    - ERDBV = 0 hours - Min board
- Designer
  - DECAD =
    - DECADF = 84 hours
    - DECADV = 50.1 hours
  - DEDB =
    - DEDBF = 42 hours
    - DEDBV = 193.6 hours
- Drafter
  - DRCAD =
    - DRCADF = 120 hours
    - DRCADV = 0 hours - Min CAD
  - DRDB =
    - DRDBF = 60 hours
    - DRDBV = 270 hours - Max board

The reduced costs of ERDBV equal to $10/hr means that if the engineers drafting billing rate were reduced to $40/hr, one hour of drafting time could be introduced without affecting the objective function. With the given resources, at $40/hr, work on the drafting board is competitive with work done on CAD. If one hour of drafting time was forced into the engineers equation without first reducing the billing rate, the objective function would deteriorate at the rate of $10/hr. Similarly, the reduced cost of $3/hr for the drafter on the CAD means, the objective function would decrease by $3 for every hour of CAD forced into the drafting equation. If the drafting CAD billing rate were reduced to less than $49/hr, CAD drafting would become more cost effective. The DRCADV variable would begin to increase as the DRDBV decreased.

From the appendix, the project managers coefficient sensitivity is shown below.

Variable	Current Coefficient	Allowable Increase	Allowable Decrease
PMCS	90.0	Infinity	20.0
PMOUT	71.0	Infinity	1.0
PMDO	70	1.0	76.8

Project Managers equations for billable dollars:

($90/hr) PMCS + ($70/hr) PMDO + ($71/hr) PMOUT

PM = .04 PSIZE = .04 (2000) = 80 hours

PMCS = (.1)(80) = 8 hours
PMDO = (.4)(80) = 32 hours
PMOUT = (.4)(80) = 32 hours
72 hours = 90% of PM

The remaining 10% of the project managers time is local slack.

In order to minimize the objective function, the 10% local slack will be allocated to the task with the lowest billed rate. The results of the linear program confirm this as follows.

($90/hr) PMCS	+	($70/hr) PMDO	+	($71/hr) PMOUT	= PM
8 hrs		32 hrs + 8 hrs(slack)		32 hrs	= 80 hrs

The project manager is required to put in at least 8 hours on the computer station (PMCS). The "Infinity" under the allowable increase heading, means the billing rate can be increased from $90/hr to infinity without affecting the distribution of the decision variables. This is true because the PMCS has the highest coefficient of all the project managers tasks and the project manager must spend at least 10% of his time at the computer station. However, if the billing rate were increased to infinity, the project costs would quickly approach infinity also. The $20/hr allowable decrease means the billing rate can be reduced to $70/hr without affecting the variable spread. At $70/hr, PMCS has the same billing rate as PMDO. If the billing rates were the same, the 8 hours slack may move from PMDO to PMCS.

The same reasoning can be applied to the coefficients relating to the project manager's time out of the office (PMOUT). Since the project manager was required to spend at least 32 hours out of the office, the billing rate could theoretically go to infinity without affecting the variable spread. By decreasing the billing rate by $1/hr the rates for PMOUT and PMDO become equal. If the billing rates were the same, the 8 hours local slack may move from PMDO to PMOUT.

The $1/hr allowable increase for PMDO means the billing rate can be increased to $71/hr (equal to PMOUT) without changing the optimal values of the decision variables. If the billing rate were increased beyond $71/hr, the 8 hour local slack would move to the PMOUT variable.

The most interesting part of the project manager's coefficient analysis, concerns the $76.81/hr allowable decrease for the project manager at the desk. Recall the billing rate for PMDO is $70/hr. If this was decreased by $76.81/hr, a negative coefficient would result. This means that for every hour the project manager spends at the desk, he must pay $6.81.

Recall, this model was created with both global and local slack values. The local slack was distributed within the disciplines between the tasks. The global slack was distributed to the discipline with the lowest weighted billing rate. The weighted billing rate for the project manager was determined as follows:

$$\$90/hr(.1)+\$70/hr(.5)+\$71/hr(.4)=\$72.4/hr$$

The .1, .5, and .4 come from the task and local slack allocation. (See table 1) Similarly, the weighted billing rate for the drafter is:

$$\$52/hr(.2)+\$47/hr(.05)+\$27/hr(.55)+\$27/hr(.2)=\$33/hr$$

Since the drafter has the lowest weighted billing rate, the global slack will be allocated to the drafter.

The linear program was re-run with a -$6.90/hr billing rate (see appendix). It was discovered that by using -$6.90/hr, the lowest weighted billing rate changed from the drafter to the project manager. Since the project manager now had the lowest weighted billing rate, the global slack moved from the drafting to the project management discipline. With the global slack now at the project managers level, the optimal values of the decision variables changed. What this means is, the project managers desk only billing rate can be crudely under estimated without a major impact on the spread of the decision variables, but it can not be overestimated by more than $1/hr. The billing rate appears to be sensitive in only one direction.

From the appendix, the engineers coefficient sensitivity is shown below.

Variable	Current Coefficient	Allowable Increase	Allowable Decrease
ERCAD	75.0	20.0	80.0
ERCS	70.0	Infinity	30.0
ERDB	50.0	Infinity	10.0
ERDO	50.0	Infinity	10.0
EROUT	51	Infinity	11.0

Engineers equations for billable dollars:

($75/hr)ERCAD+($70/hr)ERCS+($50/hr)ERDB+($50/hr)ERDB+($51/hr)EROUT

ER = .2 PSIZE = (.2)(2000) = 400 hours

ERDO = (.35)(400) = 140
EROUT = (.25)(400) = 100
ERCS = (.15)(400) = 60
ERDBF = (.09)(400) = 36
ERCADF = (.01)(400) = 4
340 hours = 90% of ER

The remaining 10% of the engineers time is local slack.

The $20/hr allowable increase for ERCAD means the billing rate for the engineer on the CAD can increase up to $95/hr without changing the variable spread. If the rate climbs above $95/hr then the CAD becomes less cost effective when compared with the drafting board billing rate. This will change the CAD/drafting board variable hour distribution. The $80/hr allowable decrease would change the billing rate to -$5/hr. This is the same scenario as the project managers negative billing rate. If the billing rate were -$5 per hour, the engineers weighted billing rate would be less than that of the drafters. Recall that the global slack goes to the discipline with the lowest average billing rate. Therefore, the engineer would pick up all the global slack and the variable hour distribution would change.

The engineer's CAD billing rate does not appear to be very sensitive. If it is estimated within +$20/hr or -$80/hr of the true value, the variable hour distribution will not change.

Although the sensitivity seems to favor under estimating as opposed to overestimating, it is not as restrictive as the project managers range of coefficients. If the billing rates for the different disciplines are spread out over a wide range, the sensitivity becomes less. The reason for this is because the global and local slack will not readily switch to another task if the billing rate changes by a small amount.

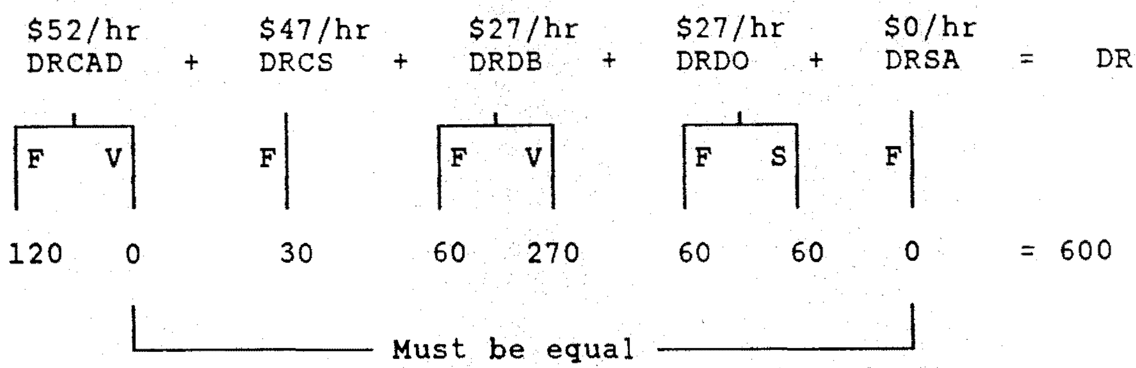
For the project as a whole, the average weighted billing rate equals $39/hr. The average billing rate of the project was determined by dividing the value of the objective function by the total number of hours. ($78,417/2000 hours).

It is interesting to note that for ERCS, ERDB, ERDO and EROUT, if the allowable decrease is applied to the billing rates, the revised billing rate will equal $40/hr for each case. For example, EROUT, the lowest billing rate, will be $51/hr - $11/hr = $40/hr. This means that as long as the billing rate is greater than the average project billing rate, there is no possibility of reallocating the slack and changing the variable distribution. It appears the sensitivity of the billing rates is closely related to how far away the billing rates are from the average project billing rates. The further the billing rates are from the average project billing rate, the less sensitive they become.

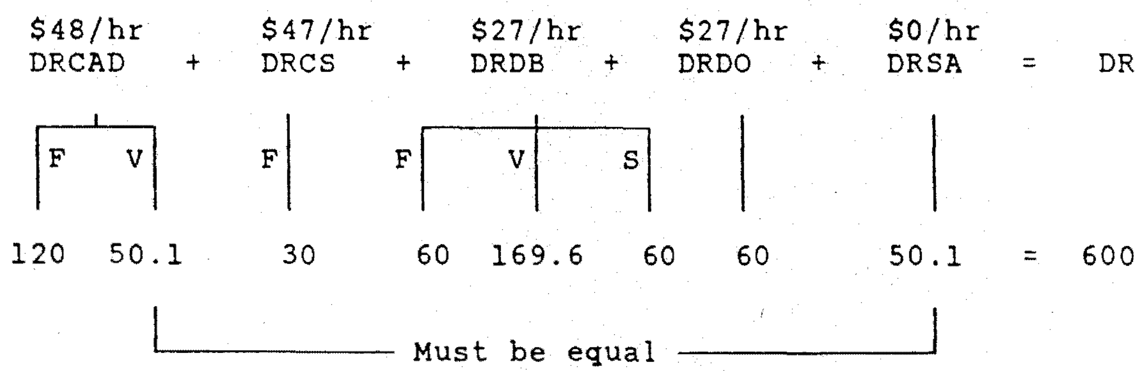
Another interesting aspect of the objective coefficient analysis concerns the relationship between the disciplines for CAD resources.

Variable	Current Coefficient	Allowable Increase	Allowable Decrease
ERCAD	75.0	20.0	80.0
DECAD	55.0	3.0	10.75
DRCAD	52.0	10.75	3.0

The variables in this program may be classified as F = Fixed, V = Variable and S = Slack. Below is the equation for the drafter. It shows both the billing rate, and how the hours were distributed among the variables. This clearly shows that all the variable hours were distributed to the drafting board and none were assigned to the CAD.



The tabulated results above indicate the CAD costs for the draftsmen can be reduced by $3/hr without affecting the variable resource distribution. The program was re-run with a $48/hr drafting CAD billing rate (see appendix). The first observation is that the CAD billing rate now became more cost effective, and 100 hours of the drafting board variable time moved to CAD variable time. Since there is a 2 to 1 productivity ratio, only 50 hours are actually charged. The other 50 hours show up under DRSA (drafting hours saved).



Recall that CAD is a limited resource and the minimization program seeks to allocate CAD hours to the discipline with the highest weighted billing rate in order to save more money. Initially, the program would give CAD hours to engineers first and to drafters last. The result of this is summarized as follows.

	CAD	Draft Board
1. Engineer variable hours	x	
2. Designer variable hours	x	x
3. Drafter variable hours		x

It can be seen that the CAD resources are depleted at the designer level and drafting board hours must be utilized. No CAD hours are available for the drafter to use.

It was stated above that for the drafter, 100 hours of drafting board variable time switched to CAD variable time, if the billing rate was reduced by $3/hr. In order for this to be possible, the designer had to free up his CAD variable time since this was a limited resource. Therefore, the CAD allocation priority changed from Engineer, Designer, Drafter to Engineer, Drafter, Designer.

	CAD	Draft Board
1. Engineer variable hours	x	
2. Drafter variable hours	x	x
3. Designer variable hours		x

The $10.75/hr allowable increase for DRCAD means that if the billing rate were greater than $62.75/hr, the average weighted billing rate would change. If this happened, the global slack would be changed from the drafter to the designer.

The $10.75/hr allowable decrease for the designer is interpreted the same way. The weighted billing rate would change and then the global slack distribution would change. The $3/hr allowable increase for the designer states that if the designer CAD rate was greater than $58/hr, it would be more cost efficient to have the variable work done on the board.

The billing rates of the various disciplines for the use of CAD is quite sensitive to change. This sensitivity can be justified because of several factors. First, CAD is a limited resource with a 2 to 1 productivity factor over manual drafting. It only makes sense that the billing rate associated with it would be sensitive. Because CAD is the highest task billing rate, and it is more productive than the board, it only takes a small change in the rate to affect the weighted discipline billing rate. The global slack variable will then go to the discipline with the lowest weighted discipline billing rate.

DUAL PRICES AND RIGHTHAND SIDE RANGE

The project size has a dual price of -$39.93 and the righthand side range is defined as +422 and -503. For every hour added, the objective function will increase/decrease by $39.93. Therefore the model is very sensitive to increases/decreases of total hours to the project. The actual rate of change of $39.93/hour will stay constant over the range of 1497 to 2422 hours. Therefore the model is somewhat insensitive to the cost/hour charge a customer may be billed, if the size of the project varies.

The project managers tasks are modeled as follows:

```
4)  PM - .04 P_SIZE >= 0             ! REQUIRES 4% OF TOTAL HOURS
5)  PMCS + PMDO + PMOUT - PM = 0      ! TOTAL PM HOURS
6)  PMCS - .10 PM >= 0                ! @ COMPUTER
```

7) PMDO - .40 PM >= 0 ! @ DESK
8) PMOUT - .40 PM >= 0 ! OUT OF OFFICE

Simplifying the above equation and add in slack/surplus variables:

Equation	Conditions	Dual	Inc.	Dec.
4) $PM - P_1 = .04(2000) = 80$	--> $P_1 = 0$	-38	200	80
5) $PMCS + PMDO + PMOUT = 80$		-70	INF.	8
6) $PMCS - P_2 = .10(80) = 8$	--> $P_2 = 0$	-20	8	8
7) $PMDO - P_3 = .40(80) = 32$	--> $P_3 = 8$	-1	8	32

The most sensitive constraint for the project manager is row 5, the definition of PM's total hours. Any change to the hours in this row will reflect a $70/hr change to the objective function. The hourly rate is valid from infinity to 72 hours. The sensitivity of the project manager's portion of the total job is critical to this model. If a 1 percent change is made, then the change in hours would be .01(2000) = 20 and the change to the objective function would be 20 * 38 = $760. Of all the different disciplines in the model, the project manager was the most sensitive to incorrect assignments of the total hours. In this model the amount of time required for the project manager is small (4% of total hours). This minimized the possible error and the sensitivity of this assumption. If the project managers hours were to vary from 0 to 9.5% of the total hours, the objective function would vary by only 5%. The sensitivity of each discipline based on a one percent error of the hourly assignment can be summarized as follows:

Group	Cost
Project Manager	$760
Engineer	$360
Designer	$43
Drafter	$0
Secretary	$60

The number of CAD stations affects the cost of a project substantially with a dual price of $720/station and a righthand side range of +.67 and -.35. This dual price is large and valid over a very small range where the number of CAD stations were fixed at two. Several runs of the LINDO program varying the number of CAD stations proved the critical nature of this variable (see figure 1). From the figure, the dual price is calculated at 1.2 CAD stations to be $30,000 per CAD station. This equates to the slope of the line at that value. This means for an increase of 1/10 of a CAD station, and will reduce the objective function by $3,000. Once the number of stations climbs over 3.9, the dual

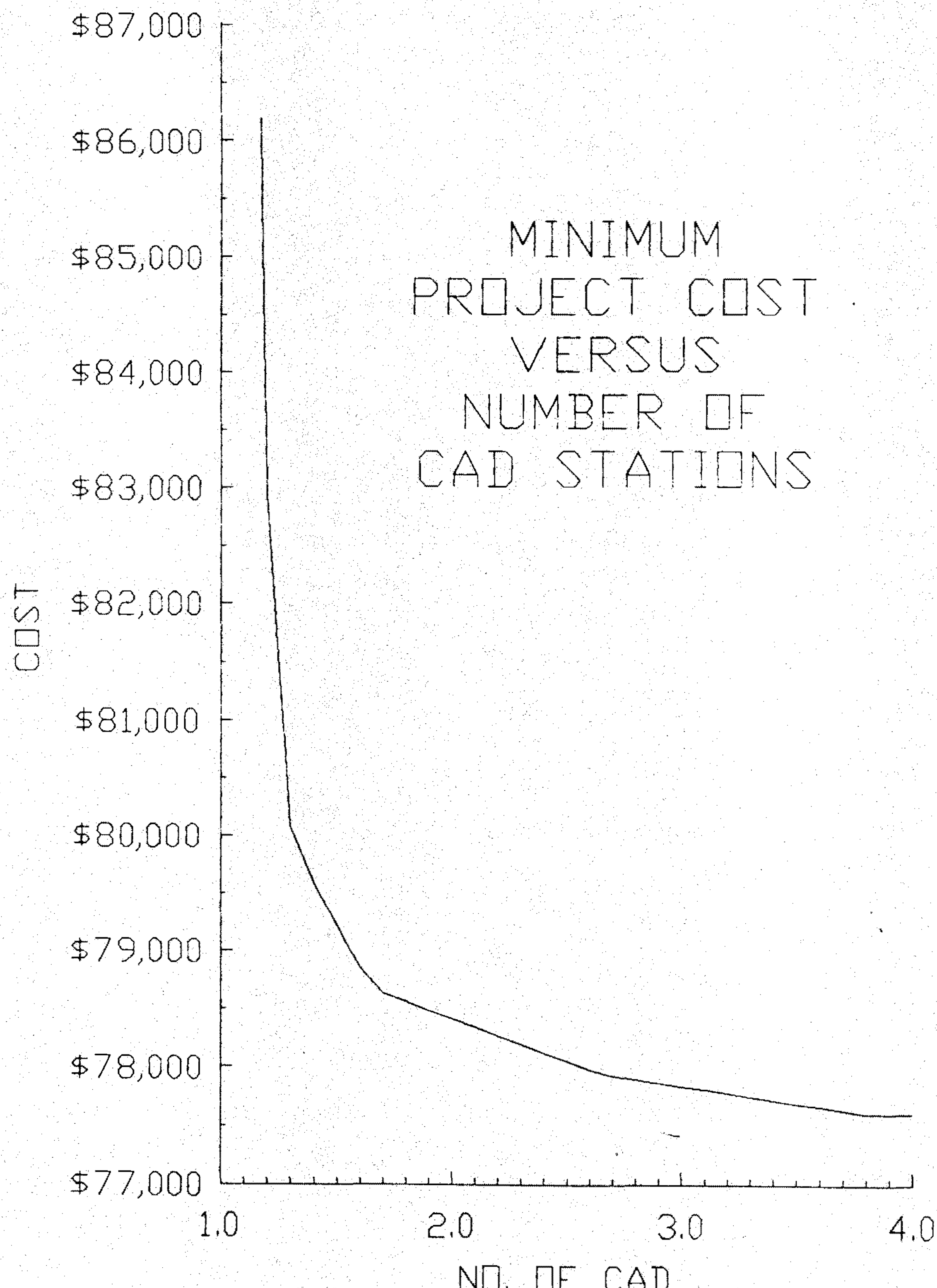

MINIMUM
PROJECT COST
VERSUS
NUMBER OF
CAD STATIONS
COST
$87,000
$86,000
$85,000
$84,000
$83,000
$82,000
$81,000
$80,000
$79,000
$78,000
$77,000
1.0
2.0
3.0
4.0
NO. OF CAD

Figure 1

price drops to zero and additional CAD stations will reduce the objective function. This model is sensitive to the number of CAD stations available. Therefore extra time should be spent on verifying the availability of CAD stations. An error of just two tenths of a CAD station could produce an error of 5% or more in the objective function. It is conceivable for the number of CAD stations on a particular project to be a continuous variable. For example, if a company was involved in 5 different projects each requiring 2.33 CAD stations, the total company demand for CAD stations would be 7. It is common for CAD resources to be shared between projects within a company.

The sensitivity of the number of CAD stations available, based on an error of one tenth of a CAD station is summarized below.

No. of CAD Stations Estimated	Actual No.	Cost
1.2	1.3	$2858
1.5	1.6	$360
2.0	2.1	$72
3.0	3.1	$28
4.0	4.1	$0

The CAD productivity constraint controls the amount of variable CAD time that is used. The CAD productivity ratio for this model is defined as 2 drafting hours equals one CAD drafting hour. The productivity equations effects the engineers, designers and drafters as defined on lines 16, 27 and 37 respectively.

The sensitivity of the CAD productivity ratio can best be evaluated from figure 2. The graph was developed by varying the productivity ratios, running the LINDO program and recording the results. The dual price and righthand side range for a productivity ratio of 2 can be calculated as $2,500 with an increase range of infinity and a decrease range of 0.2. The graph also shows a zero dual price region, where the productivity ratio has to be at least 1.5 before the objective function is affected. If the productivity is below 1.5 then the CAD stations will not be cost effective, therefore not utilized. The dual price of $2,500 is substantial, therefore it is critical to know what the minimum productivity ratio is before the project is started.

DISCUSSION OF RESULTS

According to LINDO, the minimum cost for this particular project was $78,417. This value was dependent on the estimated project size, the billing rates, the task and discipline splits, the number of CAD stations available, and the CAD drafting board productivity ratio. The objective function is very sensitive to a change in the

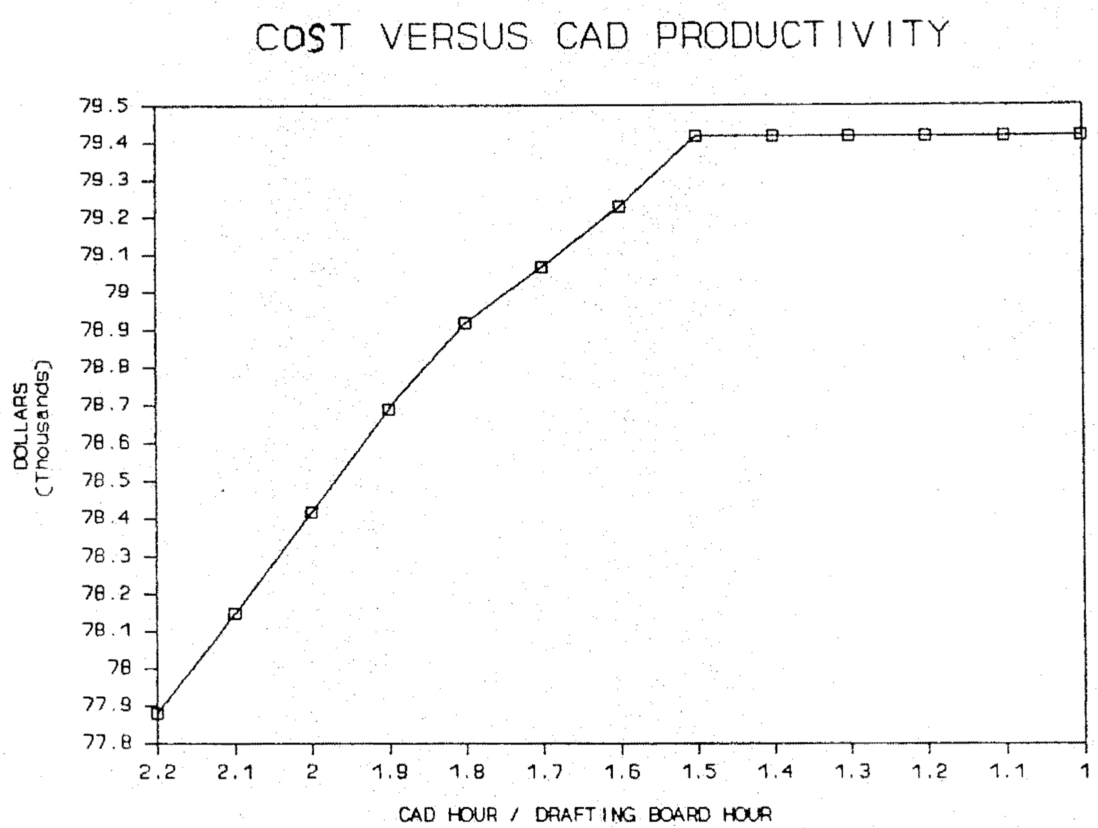


Figure 2

total number of manhours. The optimal basis will not vary much if the project size is inaccurately estimated, but the value for the objective function is subject to drastic changes.

From the sensitivity analysis, it was determined that as the discipline billing rates deviated farther from the average project billing rate, they became less sensitive. Therefore it is more critical to accurately estimate the billing rates for the designer and drafter, than for the project manager and the engineer. This seems reasonable because the designers and drafters are assigned a much larger percentage of the total job. The sensitivity of the discipline splits is directly related to the average billing rate. The project manager has a higher average billing rate, and therefore is more sensitive to a change in the hours allocated. The drafters have a much lower average billing rate and therefore are less sensitive to errors in the allocation of hours. The task splits are directly related to the discipline splits. It is therefore critical to accurately estimate how the project manager and engineer will be spending their time.

The most sensitive constraints were the number of CAD stations available and their productivity ratio. As the productivity ratio increases, the sensitivity of the number of CAD stations also increases. If one wishes to obtain an accurate estimate of the project costs, it is vital that the number of CAD stations and the productivity ratio be correct.

The parameters to be accurately estimated can be summarized as follows:

1. CAD/drafting board productivity ratio.

2. CAD stations available.

3. Total project size.

4. Percent of total work to be allocated to project manager and engineer.

5. Billing rates for designer and drafter.

CONCLUSION

Minimizing engineering costs for the client in design projects is a never ending task. In a competitive engineering environment, increasing quality and reducing costs are the keys to a successful business. This is where the proper use of Computer Aided Design creates much interest. Applied correctly, CAD can increase drafting quality productivity over manual drafting methods.

The LINDO model was based on actual industry CAD productivity rates, labor rates and the amount of time spent on a project. The results were extremely rewarding. Most values were insensitive to small changes. Sensitive values like CAD productivity, and the number of CAD stations available, were verified due to their critical nature. Other interesting aspects developed from the results, were the average hourly rates of each discipline and the overall project. These weighted hourly rates allows the project manager to easily estimate job extras.

The model did not consider environmental, political and personnel factors due to their unpredictable responses and model size limitations. Although the model does not deal with some of these intangible factors, this model focuses on the real issue, that is to minimize the project cost. Not always are our intuitive decisions correct. This model showed how incredibly sensitive a project is to CAD station availability and productivity. The model was also successful in showing the most cost effective allocation of hours with the given constraints. It also displayed where time should be spent when determining parameters to be used in an estimate.