Title: A Linear Programming Model for Determining a Product Outsourcing Strategy as a Factory Planning Tool

Course:
Year: 1991
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Report No: P91006

Abstract: This report develops a Linear Programming Model as a factory planning tool to determine a product outsourcing strategy which will maximize the number of products built in house. The monthly requirements for a number of products were considered, and an optimal in-house/out-house product build schedule was determined. The schedule was subject to various technical work center constraints and corporate strategies. Sensitivity analyses were performed to study the effects of changes in total available processing time, changes in the individual lot processing times in the various work centers, and changes in forecast demand. For work centers with slack processing time, it was found that increasing the total available processing time or decreasing the lot processing time had no economic value. The present tools can be used to study the effects of changing demand during the month, to assist in capital requirement formulations and as an interactive tool to study the effect of various "What If" scenarios.

A LINEAR PROGRAMMING MODEL FOR DETERMINING A PRODUCT OUTSOURCING STRATEGY

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EMP-P9106

Executive Summary

A factory planning tool was developed to determine a product outsourcing strategy which will maximize the number of products built in house. A linear programming model was developed which used the monthly requirements for a number of products and calculated the optimal in-house/out-house product build schedule. The schedule was subject to various technical workcenter constraints and corporate strategies. A sensitivity analysis was performed to study the effects of changes in total available processing time, changes in the individual lot processing times in the various workcenters, and changes in forecast demand. For workcenters with slack processing time, it was found that increasing the total available processing time or decreasing the lot processing time had no economic value. The present tool can also be used to study the effects of changing the demand during the month, to assist in capital requirement formulations and as an interactive tool to study the effect of various "What If" scenarios.

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Abstract

A linear programming model is presented to determine a product outsourcing strategy for j products, based upon the forecasted monthly requirements for the products, several technical constraints and various corporate strategies. A sensitivity analysis was performed to study the effects of changes in total available processing time, changes in the individual lot processing times in the various workcenters, and changes in forecast demand. For workcenters with slack processing time, increases in the total available processing time and decreases in the lot processing time were found to have no economic value. Computational results are provided for a four-month forecast period.

Introduction

A factory planning tool was developed to determine a product outsourcing strategy which will maximize the number of products built in house. A linear programming model was developed which took the monthly requirements for a number of products and calculated the optimal in-house/out-house product build schedule. The build schedule is subject to various technical workcenter constraints and corporate strategies. A sensitivity analysis will study the effects of changes in total available processing time, changes in the individual lot processing times in the various workcenters and changes in forecast demand. The present model can also be used to study the effects of changing the demand during the month, to assist in capital requirement formulations and as an interactive tool to study the effect of various "What If" scenarios.

Objectives

The primary objective of the present project is to develop a factory planning tool to determine a product outsourcing strategy which maximizes the number of products built in house while meeting the corporate objectives listed below. The tool will be forward looking, using the marketing forecast to set the build strategy three months in advance.

Other objectives of the present project include:

- develop a real-time analysis tool to verify the effects of actual monthly requirement and to assist in developing the build strategy for the coming month

- assist in the development of the yearly capital plan to support the corporate strategy regarding outsourcing

- develop a tool for analyzing "What If" scenarios which could occur (e.g., purchase of new equipment, unexpected downtime, scheduling of new products, etc.)

- determine those workcenters which are limiting production and require close monitoring

- determine the effect of sequentially processing lots of the same product to reduce set-up times

Corporate Strategy Constraints. The model of the present situation is affected by a number of corporate requirements. First, to maintain product familiarity, a minimum of 500 boards (5 lots) per month will be built in house. Second, if the monthly build rate exceeds 1000 boards (10 lots), a minimum of 5 lots will be built through outsourcing to limit the risk of missed deliveries due to excessive downtime or machine failure and to maintain a back-up supplier for the product. Third, products containing sub-0.025" pitch components must be built in house since the subcontractor does not the proper technology available to produce the boards. Fourth, a consistent in-house labor force size and work schedule is to be maintained by outsourcing any excess requirements beyond the minimum demands of the market. Overtime is not considered to be an available resource because it is generally held as a contractual reserve in case of increased customer demand and as a buffer against excessive equipment downtime. Fifth, it is desired to maintain an average of less than 20 percent outsourcing relative to the previous constraint.

Taking into account the above constraints, the objective of the present project is to develop a linear programming model for optimizing the line usage rate for a set of required products. The inputs to the model are the number of lots of products to be run during the next month. The output of the model is the optimal product mix which will allow the most boards to be produced in house (and therefore minimize the number of boards which must be produced at an outside facility).

A sensitivity analysis of the results is performed to determine the critical constraints of the systems so that recommendations regarding the line can be made. This analysis will also look at the effect of the requirements for the products changing, the need for possible capital procurement, and the effect of additional production time.

Problem Definition

The present project relates to a manufacturing facility responsible for the assembly of PC platforms. The planning tool developed will determine the optimum product mix and volume for PC baseboards which will be produced in house and outsourced.

The production line for assembling the baseboards consists of four workcenters: (1) primary side surface mount technology (SMT) assembly with two independent lines each operating 13.6 hours/day; (2) autoinsertion with two machines in parallel operating for 12 hours/day and one machine operating independently for 12 hours/day; (3) secondary side surface mount technology assembly with four lines each operating 13.6 hours/day; and (4) manual assembly/wavesolder with two lines operating 6.8 hours/day. The products are generally processed continually through the four workcenters, although some products bypass certain workcenters.

TABLE 1: MONTHLY PROCESSING TIME
AVAILABLE BY WORKCENTER (HOURS)

Primary SMT	540
Autoinsertion	480
Sec. SMT	1040
Manual Assembly	260

TABLE 1 shows the average amount of time (in hours) available in each of the workcenters per month, based on the up-time of each machine multiplied by the number of shifts per month.

TABLE 2: PROCESSING TIMES BY WORKCENTER (100 BD. LOTS)

Workcenter\Product	1	2	3	4	5	6	7	8
Primary SMT	3.2	1.2	4.6	2.6	0.5	4.1	3.8	0
Autoinsertion	1.1	2.8	0	0	3.2	0.3	0	4.5
Secondary SMT	4.5	4.2	0	4.1	3.4	6.5	0	4.2
Manual Assembly /Wavesolder	0.8	0.4	1.1	1.1	1.9	0.8	1.2	0.4

Presently, the factory produces eight products, 1 - 8. TABLE 2 shows the amount of time (in hours) required to process a lot of each of the current products through each workcenter. The product is processed in lots of 100 boards. A time of zero denotes that the product does not require processing through a particular workcenter. It is assumed that the line is balanced and in a steady state condition. Therefore, production can be finished up with the next month's allotted time.

The processing times listed in TABLE 2 include both set-up time and actual processing on a per lot basis. It may be possible to reduce the total processing time by adopting a scheduling system which would allow multiple lots of the same product to be run in order on the machines, thus avoiding excess equipment set-ups. This possibility is explored in the sensitivity analysis, but the determination of an appropriate scheduling sequence is beyond the scope of this study.

As the line is currently operated, there is always a queue of products waiting to be processed at each machine in each line. There is no unused machine time between product lots since the set-up time was included in the lot processing time. Since the machines are not physically linked, a product can easily bypass unnecessary machine steps. The lot-processing sequence at present appears to be at random or according to a specific due date requirement.

TABLE 3: FORECAST BUILD RATES (NUMBER OF LOTS)

	June	July	Aug.	Sept.
Product 1	12	20	40	60
Product 2	7	10	40	60
Product 3	25	25	30	30
Product 4	10	13	25	25
Product 5	40	40	35	35
Product 6	70	75	30	25
Product 7	30	25	25	35
Product 8	45	50	25	10

TABLE 3 shows the expected build rate (in number of 100-board lots) for the months of June to September. These build rates are based on the company's product requirements forecasts (PRF) which is usually made available immediately prior to the start of a month's production.

Literature Search

Production planning tools are used to determine the production, inventory and work force levels necessary to meet fluctuating demand requirements. Normally, the physical resources of the firm are assumed to be fixed during the planning horizon of interest, and the planning effort is oriented toward the best utilization of those resources given the external demand requirements. [Hax 1978][1] The forecast for demand over a predetermined planning horizon provides the input for determining aggregate production and work force levels for the planning horizon. This aggregate plan can then be translated into a master production schedule (MPS). [Nahmias (1989][2] Proper scheduling of the jobs is important in meeting the production goals set by the aggregate plan.

When all of the cost functions are linear, there can be a linear programming formulation to this type of planning problem. The present problem has been formulated as a linear program and solved using the LINDO system developed by Schrage [1989][3].

Linear Programming Model

In modeling the above situation as a linear programming model, the total number of loaded boards produced in house (X_j) is sought to be maximized. This will assure that the machines are being used to their full capacity and that the smallest number of boards will have to be produced at an outside facility. This objective function is expressed in Equation (1) of the model.

The cost of the products is not taken into account in the objective function since the profit margin does not vary substantially between products which are produced in house and those which are outsourced. The outsource price may be somewhat cheaper than the cost of producing the boards in house, but the corporate strategy of a constant work force takes precedence.

The model assumes that a product build schedule can be worked out to make maximum use of the available machine time. This appropriateness of this assumption will be discussed in the Discussion section, below. It is also assumed that any excess capacity time cannot be used to start the next month's required production since it is not desired to hold inventory in the factory.

Equations (2), (3), (4) and (5) of the model represent the constraints based on the amount of time available in each workcenter per month with respect to the boards produced in house (X_j). Equation (2) relates to primary side SMT, equation (3) relates to autoinsertion, equation (4) relates to secondary side SMT, and equation (5) relates to manual assembly/autoinsertion.

The program tool asks for the total demand T_j for the boards. The total demand T_j is equal to the number of boards produced in house (X_j) plus the number of boards outsourced (A_j), as defined in equation (6), below.

To retain product familiarity, it is company policy that at least five lots of each product are loaded in house each month. This lower-bound constraint is expressed in Equation (7) below. In addition, all lots of some products need to be built in house due to special technology. For example, all lots of Product 1 need to be built in house. This is expressed in Equation (8).

A further constraint which is dealt with outside of the model is that if a product is built at a run rate of 10 lots or more, at least 5 lots of the product must be built outside to provide a backup source. Further, if the product contains sub-0.025" pitch components, all of the product must be built in house. These constraints are expressed in Equation (9) below and dealt with in the user interface program (discussed below) (which calls LINDO).

As in any linear programming model, all of the variables must be nonnegative. This constraint is expressed in Equation (10) below.

REQUIRED VARIABLE DATA:

Let: I = number of workcenters

J = number of products to be produced in a month

T_j = total number of units required for product j

X_j = number of units of the jth product assembled in house

A_j = number of units of the jth product to be outsourced

C_{ij} = hours required in the ith workcenter for the jth product

OBJECTIVE FUNCTION:

$$\max z = \sum_{j=1}^{J} X_j \tag{1}$$

SUBJECT TO:

$$\sum_{j=1}^{J} C_{1j}X_j \le 540 \tag{2}$$

$$\sum_{j=1}^{J} C_{2j}X_j \le 480 \tag{3}$$

$$\sum_{j=1}^{J} C_{3j}X_j \le 1040 \tag{4}$$

$$\sum_{j=1}^{J} C_{4j}X_j \le 260 \tag{5}$$

The full model follows:

Maximize $z = X_1 + X_2 + X_3 + X_4 + X_5 + X_6 + X_7 + X_8$ (1)

S.T.

$3.2X_1 + 1.2X_2 + 4.6X_3 + 2.6X_4 + 0.5X_5 + 4.1X_6 + 3.8X_7 + 0X_8 \le 540$ (2)

$1.1X_1 + 2.8X_2 + 0X_3 + 0X_4 + 3.2X_5 + 0.3X_6 + 0X_7 + 4.5X_8 \le 480$ (3)

$4.5X_1 + 4.2X_2 + 0X_3 + 4.1X_4 + 3.4X_5 + 6.5X_6 + 0X_7 + 4.2X_8 \le 1040$ (4)

$0.8X_1 + 0.4X_2 + 1.1X_3 + 1.1X_4 + 1.9X_5 + 0.8X_6 + 1.2X_7 + 0.4X_8 \le 260$ (5)

$X_j + A_j = T_j$ for all $j = 1$ to J (6)

$X_j \ge 5$ for all $j = 1$ to J (7)

$A_1 = 0$ (8)

If $X_j > 10$, then $A_j \ge 5$ for all $j = 1$ to J (but if A_j contains sub-0.025" pitch components, then $A_j = 0$) (9)

$X_j, A_j, T_j \ge 0$ for all $j = 1$ to J (10)

User Interface Tool

The present model was prepared for use on LINDO, which is the fastest method to calculate the present build requirements. However, due to the presence of some of the corporate strategies, the model was not in the proper form for direct LINDO calculations. It was noted that the person who needs the build schedule information may not be an expert in Operations Research and should not have to learn to use this mathematical program tool. Therefore a simple user interface tool which calls the LINDO package was developed to simplify use of the present model.

The user interface in written in the C language and a copy of the program is shown in Appendix A. Under normal usage, the changes which will be input by the user are the right-hand side values for the forecast build rate constraints. The interface program reads in the demand data from a table and then asks which product build requirements needs changing. Once this information is finalized, the LINDO report is generated and the standard output is written to a file. The file can be read or printed by the user.

It is recommended that the following changes to the package be considered as a phase-II project. The current output is in LINDO format and a routine should be written to produce an output file that can be integrated into a spreadsheet for graphing the results. The user interface could also be enhanced to allow the technological coefficients of the various workcenters to be changed. Most importantly, it is recommended that the program be expanded to take advantage of the information already stored in company databases, such as the MRP and MPS databases. This would allow easy access to the forecast build requirements and allow the user to modify them for "What If" possibilities.

Solution

Copies of the LINDO printouts showing the results of the model for the months are attached as Appendices B - E. The product build schedule is summarized in Table 4, below.

TABLE 4: PRODUCT BUILD SCHEDULES FOR JUNE - SEPTEMBER
(X = Lots of boards built in house,
A = Lots of boards outsourced)

	June X	June A	July X	July A	Aug X	Aug A	Sept X	Sept A
Product 1	12	0	20	0	40	0	60	0
Product 2	7	0	5	5	35	5	55	5
Product 3	19.17	5.83	14.93	10.07	25	5	5	25
Product 4	10	0	8	5	20	5	20	5
Product 5	35	5	35	5	30	5	30	5
Product 6	65	5	70	5	25	5	19.03	5.97
Product 7	25	5	20	5	20	5	30	5
Product 8	40	5	45	5	20	5	5	5

TABLE 5 below shows the amount of slack remaining in each of the workcenters for the various months. This information is presented in graphical form in APPENDIX F.

TABLE 5: SLACK TIME BY WORKCENTER

	Primary SMT	Auto Insertion	Secondary SMT	Manual Assembly
June	0	135.7	206.1	51
July	0	108.5	133.2	52.3
August	9.5	144.5	282.5	55.5
September	0	135.8	210.3	52.3

Sensitivity Analysis

A sensitivity analysis was prepared for the month of September to determine how far the coefficients and variables could change without affecting the optimality of the solution determined above. September was chosen at random; a similar analysis could be done for the other months in the model.

ANALYSIS OF RANGE ON RIGHT-HAND SIDE VALUES (b_i)

For this part of the analysis, the effect of changing the time available in the workcenters was evaluated. Since the time constraints in each workcenter are based on the maximum machine up-time, no parametric evaluation of the effects of shifting resources from one workcenter to another is required.

Range on b_1 (Primary SMT Hours). An analysis was performed to determine by how many hours the available hours in primary SMT assembly (b_1) could vary before the present solution would no longer be optimal. The range on b_1 is:

$$482.5 < b_1 < 544$$

Therefore, if the available number of hours are decreased from the nominal 540 to less than 482.5, the basis of the solution space changes. The value of the objective function also decreases. The basis will change only when the available hours fall below 482.5. When this limit is crossed, then some products that are currently manufactured off-site at the minimum required rate will increase. To demonstrate this, the problem was run twice on LINDO using the values of 484 and 480 as the number of hours available in primary SMT, with all other variables remaining constant. The following results were obtained:

ROW	CURRENT RHS	
2	484.000000	← b_1
3	480.000000	
4	1040.000000	
5	260.000000	

OBJECTIVE FUNCTION VALUE

1) 210.365900

VARIABLE	VALUE
X1	60.000000
X2	55.000000
X3	5.000000
X4	20.000000
X5	30.000000
X6	5.365853
X7	30.000000
X8	5.000000
A2	5.000000
A3	25.000000
A4	5.000000
A5	5.000000
A6	19.634150
A7	5.000000
A8	5.000000

ROW	CURRENT RHS	
2	480.000000	← b_1
3	480.000000	
4	1040.000000	
5	260.000000	

OBJECTIVE FUNCTION VALUE

1) 209.342100

VARIABLE	VALUE
X1	60.000000
X2	55.000000
X3	5.000000
X4	20.000000
X5	30.000000
X6	5.000000
X7	29.342110
X8	5.000000
A2	5.000000
A3	25.000000
A4	5.000000
A5	5.000000
A6	20.000000
A7	5.657895
A8	5.000000

As demonstrated, when the hours available in primary SMT assembly are reduced from the nominal value, the number of boards that are manufactured in-house decreases. When b_1 is changed to 484 (within the range of b_1), it does not present a serious scheduling problem. However, if the hours are decreased below the limit of 482.5, then the scheduling has to be changed because new variables enter the basis now. As seen in the first row above, X_6 is no longer in the basis and now only the minimum amount of this product is produced in house. A_7 comes into the basis and the outsourced production quantity increases and the in-house production of X_7 decreases.

From this analysis, it is obvious that the factory can afford some additional down-time (with the concomitant loss of profit) on the primary surface mount machine. However, if this down-time increases to below the limit, scheduling has to be changed.

Range on b_2 (Autoinsertion Hours). The nominal value for b_2 is 480 hours and the range on b_2 is:

$$344.2073 < b_2 < \infty$$

The upper limit on b_2 should be expected since this workcenter is not used to its full capacity this month, as indicated by its positive slack. The lower limit again poses a similar situation as mentioned above for b_1.

Range on b_3 (Secondary SMT Hours). The nominal value for b_3 is 1040 hours and the range on b_2 is:

$$829.65 < b_3 < \infty$$

Range on b_4 (Manual Assembly/Wavesolder Hours). The nominal value for b_4 is 260 hours and the range on b_4 is:

$$207.72 < b_4 < \infty$$

Range on Demand Quantity. The quantity demanded for a product can increase only if there is sufficient slack left in all applicable workcenters. If there is not enough slack, the product mix will change and the model will have to be rerun with the new demand data and a new product mix produced. If the demand goes down, either the mix will be changed or there may be additional slack at one or more of the workcenters.

ANALYSIS OF CHANGES TO THE TECHNOLOGY COEFFICIENTS (C_{ij})

The range on ~~the~~ selected technological coefficients (the processing time per lot in each workcenter) were calculated for products 1 and 7. Copies of the LINDO printout for selected technology coefficients are attached as APPENDIX G.

$$0 < \Delta C_{11} < 0$$
$$-\infty < \Delta C_{21} < 2.2632$$
$$-\infty < \Delta C_{31} < 3.5057$$
$$-\infty < \Delta C_{41} < 0.8713$$

$$0 < \Delta C_{17} < 0$$
$$-\infty < \Delta C_{27} < 4.5264$$
$$-\infty < \Delta C_{37} < 7.0014$$
$$-\infty < \Delta C_{47} < 1.7427$$

Since resource 1 (time in primary SMT) is fully consumed for this month, any increase in the technology coefficients $C_{11}..C_{18}$ means that now more resources are required than are presently available. This would make the present solution ~~infeasible~~ inoptimal and a new simplex iteration is required. Any decrease in the coefficients means that more slack is available, that is the solution is no longer optimal. Therefore the coefficients associated with constraint 1 are not allowed to change.

The constraints associated with the other workcenters (2, 3 and 4) have a positive slack associated with them. Therefore products utilizing these resources can have additional time on these machines. This time is calculated in terms of the coefficients as mentioned above. For example, each lot of product 1 can have an additional time of 2.2632 hours in workcenter 2 (autoinsertion/wavesolder). Note that for the purposes of this analysis, the technological coefficients are only allowed to change one at a time.

When the technology coefficients are decreased for a constraint that has a positive slack, it only releases more resources that have no economic value. This is demonstrated by the fact that the lower limit on the coefficients has an infinite value. This means that a decrease in the setup time for those workcenters with positive slack is a waste of resources.

Discussion of Results

From FIGURE 1, the factory bottleneck is the primary SMT line for most months since there is zero slack. If additional hours can be made available in that workcenter, the number of boards built in house can be increased. Several options are available to increase the hours, including reducing the setup time sequentially processing lots of the same product, using overtime or a 3rd shift for the primary SMT line only, or adding capital equipment to the workcenter to increase capacity. Since the range on the technological coefficients for primary SMT is zero, combining lots or adding capital to the area (because they affect only the technological coefficients) will change the optimal solution and require that LINDO be rerun to determine the new optimal solution. The right-hand side can only be increased by four hours before the solution is no longer optimal. Therefore, any significant changes made to increase the primary SMT capacity will result in a change to the optimal solution.

Also from FIGURE 1, workareas other than primary SMT have a large amount of slack time. Adding products to the build schedule that only require processing through workcenters 2, 3, and 4 could be done at no additional cost to manufacturing from a equipment utilization standpoint. If the outsourcing requirement on product 8 was dropped for the month of September, the 5 lots could be built in house at little risk for missing deliveries because of the slacks are so large. Adding products which do not require processing through workcenter 1 or eliminating the outsourcing requirement on product 8 would have no effect on the optimality of the solution, but would increase the number of boards produced in house.

The range on workcenters 2, 3, and 4 have no upper bounds since they have slacks greater than zero. This means that increasing the production hours in these areas would have no effect on the optimality of the solution. On the lower range, workcenters 1 and 4 have about the same delta variations of 57.5 hours and 53 hours, respectively. These areas will require the most amount of management attention to make sure production moves through so that the solution remains optimal. The lower bound of the ranges in the other areas are large enough that timely reaction to any equipment downtime or process problems should be possible.

The technology coefficients of the products in workcenters other than primary side SMT all have a value of negative infinity as the lower bound. This is because those workcenters have a positive slack and adding resources or capital to reduce them has no economic value.

The analysis of product requirements changes indicated that increased demand for any product that required the use of the primary SMT line would force a change in the optimal solution, meaning it would free up resources which would be consumed by other products. Any product added that did not use primary SMT capacity could be added without changing the optimal solution up to the point that it consumed the remaining slack of one of the three remaining workcenters.

Extensions

The model assumes that each product has equal value to manufacturing. While the profit margins for each product if built in house is similar, the cost of manufacturing between in house production sites and the outsourcing facility are different. Equipment differences and capacity limitations are not the same, so assuming the profit margin for a product built in house and outsourced is not a valid assumption. Price was not considered in this analysis because the costs of the various products were not available. A complete analysis would probably include this information. Adding a cost function to the objective function equation would ~~probably~~ shift the objective of the project from optimizing the number of products built in house to maximizing the profit for the month. Maximizing the profit objective would be concerned with maximizing equipment utilization and the optimal solution would not ensure a consistent workload internally.

The model also assumes a constant number of hours available in each workcenter for the month. If the time is not constant, the program could be enhanced to ask the number of available hours to make the program more responsive to the actual situation in the factory.

Additionally, the constraint of outsourcing a maximum of 20 percent of the total production build was first considered to be soft constraint mainly used for capital forecasting. While this is still true if the 20% maximum constraint is firm enough that overtime is added to the critical areas to keep additional product in house. The model will have to be updated to determine which areas will require overtime and then which product will not have to be outsourced. Since this constraint is nonlinear, it will require the use of a different modelling tool.

Conclusions

The purpose of this project was to develop a tool to determine a feasible outsourcing strategy that maximized the number of products built internally. This tool is to be used to forecast the build strategy several months in advance. As the model took form, it became evident that the original goal could be enhanced to include features such as determining the need for capital expenditures and reevaluating the present outsourcing constraints to make manufacturing more cost effective. The model can also be expanded to include additional products or additional constraints as the need arises in the future.

REFERENCES

1. Hax, Arnoldo C., "Aggregate Production Planning," Handbook of Operations Research: Models and Applications (Moder, J.J. and Elmaghraby, S.E., eds.), New York: Van Nostrand Reinhold Co., 1978, p. 127-168.

2.Nahmias, Steven, Production and Operations Analysis, Homewood, IL: Irwin, 1989, pp. 286-290.

3.Schrage, Linus, Linear, Integer and Quadratic Programming with LINDO, 4th. ed., San Francisco: The Scientific Press, 1989.

APPENDIX A

User Interface Program Listing

```
#include <signal.h>
#include <stdio.h>

#include <gfuncts.h>
#include <color.h>

float p1, p2, p3, p4, p5, p6, p7, p8, rhs;
float tp1, tp2, tp3, tp4, tp5, tp6, tp7, tp8, trhs = 0;
char constraint[400];
int change = 0;
int day_cnt;


main () {

        FILE *fp, *of, *tp;
        char *result;
        int cnt = 0;

        if (( fp = fopen ("mgmtin","r" )) == NULL ) {
                        printf( "Couldn't find mgmtin file\n\n\n");
                        exit();
        }
        of = fopen ( "mgmtout","w");
        tp = fopen ( "mgmttmp","w");
        fprintf ( of,"MAX  I1 + I2 + I3 + I4 + I5 + I6 + I7 + I8\n");
        fprintf ( of,"st\n");

        input_menu();

        while ( cnt++ < 4 ) {
                fgets( constraint, sizeof constraint, fp );
                if ( feof( fp ) ) {
                        printf ("End of file reached\n");
                        fclose( fp );
                        fclose( of );
                        fclose( tp );
                        exit(1);
                }

                format_date();
                fprintf(of,"%2.2fX1 + %2.2fX2 + %2.2fX3 + %2.2fX4 \n",
                        p1, p2 ,p3 ,p4);
                fprintf(of,"+ %2.2fX5 + %2.2fX6 + %2.2fX7"
                        " + %2.2fX8 <= %5.0f\n",p5, p6, p7, p8, rhs * day_cnt);
                fprintf(tp,"%2.2f %2.2f %2.2f %2.2f", p1, p2 ,p3 ,p4);
                fprintf(tp," %2.2f %2.2f %2.2f %2.2f %5.3f\n",p5, p6, p7, p8, rh
        }
        cnt = 0;

        fgets( constraint, sizeof constraint, fp );
        if ( feof( fp ) ) {
                printf ("End of file reached\n");
                fclose( fp );
                fclose( of );
                fclose( tp );
                exit(1);
        }
        format_date();
```

```
fprintf(of,"X2 >=  %3.0f\nX3 >= %3.0f\n"
        "X4 >= %3.0f\n",  p2, p3, p4);
fprintf(of,"X5 >= %3.0f\nX6 >= %3.0f\n"
        "X7 >= %3.0f\nX8 >= %3.0f\n",p5, p6, p7, p8);
fprintf(tp,"%3.0f %3.0f %3.0f %3.0f ",p1, p2, p3, p4);
fprintf(tp,"%3.0f %3.0f %3.0f %3.0f %3.0f\n",p5, p6, p7, p8, rhs);

fgets( constraint, sizeof constraint, fp );
if ( feof( fp ) ) {
        printf ("End of file reached\n");
        fclose( fp );
        fclose( of );
        fclose( tp );
        exit(1);
}
format_date();

if ( tp1 )  p1 = tp2;
if ( tp2 )  p2 = tp2;
if ( tp3 )  p3 = tp3;
if ( tp4 )  p4 = tp4;
if ( tp5 )  p5 = tp5;
if ( tp6 )  p6 = tp6;
if ( tp7 )  p7 = tp7;
if ( tp8 )  p8 = tp8;

if ( p2 > 10.0 )
        fprintf(of,"A2 >= 5\n");
if ( p3 > 10.0 )
        fprintf(of,"A3 >= 5\n");
if ( p4 > 10.0 )
        fprintf(of,"A4 >= 5\n");
if ( p5 > 10.0 )
        fprintf(of,"A5 >= 5\n");
if ( p6 > 10.0 )
        fprintf(of,"A6 >= 5\n");
if ( p7 > 10.0 )
        fprintf(of,"A7 >= 5\n");
if ( p8 > 10.0 )
        fprintf(of,"A7 >= 5\n");

fprintf(of,"X1 = %3.0f\nX2 + A2 = %3.0f\nX3 + A3 = %3.0f\n"
        "X4 + A4 = %3.0f\n",p1,p2, p3, p4);
fprintf(of,"X5 + A5 = %3.0f\nX6 + A6 = %3.0f\n"
        "X7 + A7 = %3.0f\nX8 + A8 = %3.0f\n",p5, p6, p7, p8);
fprintf(tp,"%3.0f %3.0f %3.0f %3.0f",p1,p2, p3, p4);
fprintf(tp,"%3.0f %3.0f %3.0f %3.0f %3.0f\n",p5, p6, p7, p8, rhs);

fclose( fp );
fclose( of );
fclose( tp );

if ( change )
        update_files();

vmode(3);

printf("Processing data\n");
system("lindo < run.bat > solution ");
printf("Finished   File 'solution' contains data analysis \n");
```

```
}

format_date()
{

        sscanf( constraint, "%f %f %f %f %f %f %f %f %f ",
                        &p1, &p2, &p3, &p4, &p5, &p6, &p7, &p8, &rhs);
}

input_menu()
{
        char buffer[36];
        char lot[12];

        vmode (16);
        ratsay ( 4, 0, WHITE, 0, "Input the number of days for the query month :

        gets(buffer);
        sscanf (buffer,"%d",&day_cnt);
        ratsay ( 6, 0, WHITE, 0, "Do you wish to change build rate for any produ

        gets ( buffer );
        if ( buffer[0] == 'Y' || buffer[0] == 'y' ) {
                while (1) {
                        ratsay( 8, 0, WHITE, 0,
                        "Enter product ID number or press 'Enter' when complete:

                        gets(buffer);
                        if ( strlen(buffer) == 0 )
                                break;
                        ratsay( 9, 0, WHITE, 0,
                        "Enter value per lot/1000 : ");

                        gets(lot);
                        switch ( buffer[0] ) {
                                case '1':
                                        sscanf( lot, "%f", &tp1 );
                                        change++;
                                        break;
                                case '2':
                                        sscanf( lot, "%f",&tp2 );
                                        change++;
                                        break;
                                case '3':
                                        sscanf( lot, "%f",&tp3 );
                                        change++;
                                        break;
                                case '4':
                                        sscanf( lot, "%f",&tp4 );
                                        change++;

                                        break;
                                case '5':
                                        sscanf( lot, "%f",&tp5 );
                                        change++;
                                        break;
                                case '6':
                                        sscanf( lot, "%f",&tp6 );
                                        change++;
                                        break;
```

```
                        case '7':
                                sscanf( lot, "%f",&tp7 );
                                change++;
                                break;
                        case '8':
                                sscanf( lot, "%f",&tp8 );
                                change++;
                                break;
                    }
                    ratsay( 8, 51, WHITE, 0,"      ");
                    ratsay( 9, 24, WHITE, 0,"      ");
            }
        }
}
update_files()
{
        char buffer[16];


        while (1) {
                ratsay( 20, 0, WHITE, 0, "Save changes (y/n)? ");
                gets(buffer);
                if ( buffer[0] == 'y' || buffer[0] == 'Y' ) {
                        system ("copy mgmttmp mgmtin");
                        break;
                } else {
                        if (buffer[0] == 'n' || buffer[0] == 'N' )
                                break;
                }
        }
}
```

APPENDIX B

LINDO Results for Production in the Month of June

NEW SCHEDULE FOR JUNE

LINDO/PC (9 AUG 89)

STUDENT EDITION - FOR ACADEMIC USE ONLY

```
: : : ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ?

:
MAX      X1 + X2 + X3 + X4 + X5 + X6 + X7 + X8
SUBJECT TO
       2)   3.2 X1 + 1.2 X2 + 4.6 X3 + 2.6 X4 + 0.5 X5 + 4.1 X6 + 3.8 X7
     <=   540
       3)   1.1 X1 + 2.8 X2 + 3.2 X5 + 0.3 X6 + 4.5 X8 <=   480
       4)   4.5 X1 + 4.2 X2 + 4.1 X4 + 3.4 X5 + 6.5 X6 + 4.2 X8 <=   1040
       5)   0.8 X1 + 0.4 X2 + 1.1 X3 + 1.1 X4 + 1.9 X5 + 0.8 X6 + 1.2 X7
     + 0.4 X8 <=   260
       6)   X1 =    12
       7)   X2 >=   5
       8)   X3 >=   5
       9)   X4 >=   5
      10)   X5 >=   5
      11)   X6 >=   5
      12)   X7 >=   5
      13)   X8 >=   5
      14)   A3 >=   5
      15)   A5 >=   5
      16)   A6 >=   5
      17)   A7 >=   5
      18)   A8 >=   5
      19)   X2 + A2 =    7
      20)   X3 + A3 =    25
      21)   X4 + A4 =    10
      22)   X5 + A5 =    40
      23)   X6 + A6 =    70
      24)   X7 + A7 =    30
      25)   X8 + A8 =    45
END

:  LP OPTIMUM FOUND AT STEP      19

       OBJECTIVE FUNCTION VALUE

       1)     213.173900
```

VARIABLE	VALUE	REDUCED COST
X1	12.000000	.000000
X2	7.000000	.000000
X3	19.173920	.000000
X4	10.000000	.000000
X5	35.000000	.000000
X6	65.000000	.000000
X7	25.000000	.000000
X8	40.000000	.000000
A3	5.826085	.000000
A5	5.000000	.000000

A6	5.000000	.000000
A7	5.000000	.000000
A8	5.000000	.000000
A2	.000000	.739130
A4	.000000	.434783

ROW	SLACK OR SURPLUS	DUAL PRICES
2)	.000000	.217391
3)	135.700000	.000000
4)	206.100000	.000000
5)	51.008690	.000000
6)	.000000	.304348
7)	2.000000	.000000
8)	14.173910	.000000
9)	5.000000	.000000
10)	30.000000	.000000
11)	60.000000	.000000
12)	20.000000	.000000
13)	35.000000	.000000
14)	.826085	.000000
15)	.000000	-.891304
16)	.000000	-.108696
17)	.000000	-.173913
18)	.000000	-1.000000
19)	.000000	.739130
20)	.000000	.000000
21)	.000000	.434783
22)	.000000	.891304
23)	.000000	.108696
24)	.000000	.173913
25)	.000000	1.000000

NO. ITERATIONS= 19

DO RANGE(SENSITIVITY) ANALYSIS?
?
RANGES IN WHICH THE BASIS IS UNCHANGED:

OBJ COEFFICIENT RANGES

VARIABLE	CURRENT COEF	ALLOWABLE INCREASE	ALLOWABLE DECREASE
X1	1.000000	INFINITY	INFINITY
X2	1.000000	INFINITY	.739130
X3	1.000000	.121951	1.000000
X4	1.000000	INFINITY	.434783
X5	1.000000	INFINITY	.891304
X6	1.000000	INFINITY	.108696
X7	1.000000	INFINITY	.173913
X8	1.000000	INFINITY	1.000000
A3	.000000	1.000000	.121951
A5	.000000	.891304	INFINITY
A6	.000000	.108696	INFINITY
A7	.000000	.173913	INFINITY
A8	.000000	1.000000	INFINITY
A2	.000000	.739130	INFINITY
A4	.000000	.434783	INFINITY

RIGHTHAND SIDE RANGES

ROW	CURRENT	ALLOWABLE	ALLOWABLE

	RHS	INCREASE	DECREASE
2	540.000000	3.799991	65.200000
3	480.000000	INFINITY	135.700000
4	1040.000000	INFINITY	206.100000
5	260.000000	INFINITY	51.008690
6	12.000000	20.375000	1.187497
7	5.000000	2.000000	INFINITY
8	5.000000	14.173910	INFINITY
9	5.000000	5.000000	INFINITY
10	5.000000	30.000000	INFINITY
11	5.000000	60.000000	INFINITY
12	5.000000	20.000000	INFINITY
13	5.000000	35.000000	INFINITY
14	5.000000	.826085	INFINITY
15	5.000000	7.599981	5.000000
16	5.000000	.926827	5.000000
17	5.000000	.999998	5.000000
18	5.000000	35.000000	5.000000
19	7.000000	48.464290	2.000000
20	25.000000	INFINITY	.826085
21	10.000000	25.076930	1.461535
22	40.000000	28.649570	7.599981
23	70.000000	15.902440	.926827
24	30.000000	17.157900	.999998
25	45.000000	30.155560	35.000000

:

APPENDIX C

LINDO Results for Production in the Month of July

NEW SCHEDULE FOR JULY

LINDO/PC (9 AUG 89)

STUDENT EDITION - FOR ACADEMIC USE ONLY

```
:  :  :  ?  ?  ?  ?  ?  ?  ?  ?  ?  ?  ?  ?  ?  ?  ?  ?  ?  ?  ?  ?  ?  ?  ?  ?

:
MAX      X1 + X2 + X3 + X4 + X5 + X6 + X7 + X8
SUBJECT TO
       2)    3.2 X1 + 1.2 X2 + 4.6 X3 + 2.6 X4 + 0.5 X5 + 4.1 X6 + 3.8 X7
     <=   540
       3)    1.1 X1 + 2.8 X2 + 3.2 X5 + 0.3 X6 + 4.5 X8 <=    480
       4)    4.5 X1 + 4.2 X2 + 4.1 X4 + 3.4 X5 + 6.5 X6 + 4.2 X8 <=    1040
       5)    0.8 X1 + 0.4 X2 + 1.1 X3 + 1.1 X4 + 1.9 X5 + 0.8 X6 + 1.2 X7
     + 0.4 X8 <=    260
       6)    X1 =     20
       7)    X2 >=    5
       8)    X3 >=    5
       9)    X4 >=    5
      10)    X5 >=    5
      11)    X6 >=    5
      12)    X7 >=    5
      13)    X8 >=    5
      14)    A2 >=    5
      15)    A3 >=    5
      16)    A4 >=    5
      17)    A5 >=    5
      18)    A6 >=    5
      19)    A7 >=    5
      20)    A8 >=    5
      21)    X2 + A2 =     10
      22)    X3 + A3 =     25
      23)    X4 + A4 =     13
      24)    X5 + A5 =     40
      25)    X6 + A6 =     75
      26)    X7 + A7 =     25
      27)    X8 + A8 =     50
END

:  LP OPTIMUM FOUND AT STEP      16

       OBJECTIVE FUNCTION VALUE

       1)     217.934800

 VARIABLE        VALUE          REDUCED COST
       X1        20.000000          .000000
       X2         5.000000          .000000
       X3        14.934780          .000000
       X4         8.000000          .000000
       X5        35.000000          .000000
       X6        70.000000          .000000
       X7        20.000000          .000000
       X8        45.000000          .000000
```

A2	5.000000	.000000
A3	10.065220	.000000
A4	5.000000	.000000
A5	5.000000	.000000
A6	5.000000	.000000
A7	5.000000	.000000
A8	5.000000	.000000

ROW	SLACK OR SURPLUS	DUAL PRICES
2)	.000000	.217391
3)	108.500000	.000000
4)	133.200000	.000000
5)	52.271740	.000000
6)	.000000	.304348
7)	.000000	.000000
8)	9.934785	.000000
9)	3.000000	.000000
10)	30.000000	.000000
11)	65.000000	.000000
12)	15.000000	.000000
13)	40.000000	.000000
14)	.000000	-.739130
15)	5.065216	.000000
16)	.000000	-.434783
17)	.000000	-.891304
18)	.000000	-.108696
19)	.000000	-.173913
20)	.000000	-1.000000
21)	.000000	.739130
22)	.000000	.000000
23)	.000000	.434783
24)	.000000	.891304
25)	.000000	.108696
26)	.000000	.173913
27)	.000000	1.000000

NO. ITERATIONS= 16

DO RANGE(SENSITIVITY) ANALYSIS?
?
RANGES IN WHICH THE BASIS IS UNCHANGED:

		OBJ COEFFICIENT RANGES	
VARIABLE	CURRENT COEF	ALLOWABLE INCREASE	ALLOWABLE DECREASE
X1	1.000000	INFINITY	INFINITY
X2	1.000000	INFINITY	.739130
X3	1.000000	.121951	1.000000
X4	1.000000	INFINITY	.434783
X5	1.000000	INFINITY	.891304
X6	1.000000	INFINITY	.108696
X7	1.000000	INFINITY	.173913
X8	1.000000	INFINITY	1.000000
A2	.000000	.739130	INFINITY
A3	.000000	1.000000	.121951
A4	.000000	.434783	INFINITY
A5	.000000	.891304	INFINITY
A6	.000000	.108696	INFINITY
A7	.000000	.173913	INFINITY

A8	.000000	1.000000	INFINITY

RIGHTHAND SIDE RANGES

ROW	CURRENT RHS	ALLOWABLE INCREASE	ALLOWABLE DECREASE
2	540.000000	23.299990	45.700010
3	480.000000	INFINITY	108.500000
4	1040.000000	INFINITY	133.200000
5	260.000000	INFINITY	52.271740
6	20.000000	14.281250	7.281247
7	5.000000	.000000	INFINITY
8	5.000000	9.934785	INFINITY
9	5.000000	3.000000	INFINITY
10	5.000000	30.000000	INFINITY
11	5.000000	65.000000	INFINITY
12	5.000000	15.000000	INFINITY
13	5.000000	40.000000	INFINITY
14	5.000000	.000000	5.000000
15	5.000000	5.065216	INFINITY
16	5.000000	3.000000	5.000000
17	5.000000	30.000000	5.000000
18	5.000000	5.682925	5.000000
19	5.000000	6.131577	5.000000
20	5.000000	40.000000	5.000000
21	10.000000	31.714290	.000000
22	25.000000	INFINITY	5.065216
23	13.000000	17.576930	3.000000
24	40.000000	29.358970	30.000000
25	75.000000	11.146340	5.682925
26	25.000000	12.026320	6.131577
27	50.000000	24.111110	40.000000

:

APPENDIX D

LINDO Results for Production in the Month of August

AUGUST

LINDO/PC (9 AUG 89)

STUDENT EDITION - FOR ACADEMIC USE ONLY

```
: : : ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ?

:
MAX      X1 + X2 + X3 + X4 + X5 + X6 + X7 + X8
SUBJECT TO
        2)   3.2 X1 + 1.2 X2 + 4.6 X3 + 2.6 X4 + 0.5 X5 + 4.1 X6 + 3.8 X7
     <=   540
        3)   1.1 X1 + 2.8 X2 + 3.2 X5 + 0.3 X6 + 4.5 X8 <=   480
        4)   4.5 X1 + 4.2 X2 + 4.1 X4 + 3.4 X5 + 6.5 X6 + 4.2 X8 <=   1040
        5)   0.8 X1 + 0.4 X2 + 1.1 X3 + 1.1 X4 + 1.9 X5 + 0.8 X6 + 1.2 X7
     + 0.4 X8 <=   260
        6)   X1 =    40
        7)   X2 >=   5
        8)   X3 >=   5
        9)   X4 >=   5
       10)   X5 >=   5
       11)   X6 >=   5
       12)   X7 >=   5
       13)   X8 >=   5
       14)   A2 >=   5
       15)   A3 >=   5
       16)   A4 >=   5
       17)   A5 >=   5
       18)   A6 >=   5
       19)   A7 >=   5
       20)   A8 >=   5
       21)   X2 + A2 =    40
       22)   X3 + A3 =    30
       23)   X4 + A4 =    25
       24)   X5 + A5 =    35
       25)   X6 + A6 =    30
       26)   X7 + A7 =    25
       27)   X8 + A8 =    25
END

:  LP OPTIMUM FOUND AT STEP     16

       OBJECTIVE FUNCTION VALUE

       1)      215.000000

 VARIABLE        VALUE          REDUCED COST
       X1        40.000000          .000000
       X2        35.000000          .000000
       X3        25.000000          .000000
       X4        20.000000          .000000
       X5        30.000000          .000000
       X6        25.000000          .000000
       X7        20.000000          .000000
       X8        20.000000          .000000
```

A2	5.000000	.000000
A3	5.000000	.000000
A4	5.000000	.000000
A5	5.000000	.000000
A6	5.000000	.000000
A7	5.000000	.000000
A8	5.000000	.000000

ROW	SLACK OR SURPLUS	DUAL PRICES
2)	9.500004	.000000
3)	144.500000	.000000
4)	282.500000	.000000
5)	55.500000	.000000
6)	.000000	1.000000
7)	30.000000	.000000
8)	20.000000	.000000
9)	15.000000	.000000
10)	25.000000	.000000
11)	20.000000	.000000
12)	15.000000	.000000
13)	15.000000	.000000
14)	.000000	-1.000000
15)	.000000	-1.000000
16)	.000000	-1.000000
17)	.000000	-1.000000
18)	.000000	-1.000000
19)	.000000	-1.000000
20)	.000000	-1.000000
21)	.000000	1.000000
22)	.000000	1.000000
23)	.000000	1.000000
24)	.000000	1.000000
25)	.000000	1.000000
26)	.000000	1.000000
27)	.000000	1.000000

NO. ITERATIONS= 16

DO RANGE(SENSITIVITY) ANALYSIS?
?
RANGES IN WHICH THE BASIS IS UNCHANGED:

		OBJ COEFFICIENT RANGES	
VARIABLE	CURRENT COEF	ALLOWABLE INCREASE	ALLOWABLE DECREASE
X1	1.000000	INFINITY	INFINITY
X2	1.000000	INFINITY	1.000000
X3	1.000000	INFINITY	1.000000
X4	1.000000	INFINITY	1.000000
X5	1.000000	INFINITY	1.000000
X6	1.000000	INFINITY	1.000000
X7	1.000000	INFINITY	1.000000
X8	1.000000	INFINITY	1.000000
A2	.000000	1.000000	INFINITY
A3	.000000	1.000000	INFINITY
A4	.000000	1.000000	INFINITY
A5	.000000	1.000000	INFINITY
A6	.000000	1.000000	INFINITY
A7	.000000	1.000000	INFINITY

A8	.000000	1.000000	INFINITY

RIGHTHAND SIDE RANGES

ROW	CURRENT RHS	ALLOWABLE INCREASE	ALLOWABLE DECREASE
2	540.000000	INFINITY	9.500004
3	480.000000	INFINITY	144.500000
4	1040.000000	INFINITY	282.500000
5	260.000000	INFINITY	55.500000
6	40.000000	2.968751	40.000000
7	5.000000	30.000000	INFINITY
8	5.000000	20.000000	INFINITY
9	5.000000	15.000000	INFINITY
10	5.000000	25.000000	INFINITY
11	5.000000	20.000000	INFINITY
12	5.000000	15.000000	INFINITY
13	5.000000	15.000000	INFINITY
14	5.000000	30.000000	5.000000
15	5.000000	20.000000	2.065218
16	5.000000	15.000000	3.653848
17	5.000000	25.000000	5.000000
18	5.000000	20.000000	2.317074
19	5.000000	15.000000	2.500001
20	5.000000	15.000000	5.000000
21	40.000000	7.916669	30.000000
22	30.000000	2.065218	20.000000
23	25.000000	3.653848	15.000000
24	35.000000	19.000010	25.000000
25	30.000000	2.317074	20.000000
26	25.000000	2.500001	15.000000
27	25.000000	32.111110	15.000000

:

APPENDIX E

LINDO Results for Production in the Month of September

SEPTEMBER

```
LINDO/PC (9 AUG 89)

COPYRIGHT (C) 1989 LINDO SYSTEMS,  INC.   PORTIONS
COPYRIGHT (C) 1981 MICROSOFT CORPORATION. LICENSED
MATERIAL,  ALL RIGHTS RESERVED.  COPYING EXCEPT AS
AUTHORIZED IN LICENSE AGREEMENT IS PROHIBITED.

STUDENT EDITION - FOR ACADEMIC USE ONLY


: : : ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ?

:
MAX      X1 + X2 + X3 + X4 + X5 + X6 + X7 + X8
SUBJECT TO
        2)   3.2 X1 + 1.2 X2 + 4.6 X3 + 2.6 X4 + 0.5 X5 + 4.1 X6 + 3.8 X7
     <=   540
        3)   1.1 X1 + 2.8 X2 + 3.2 X5 + 0.3 X6 + 4.5 X8 <=   480
        4)   4.5 X1 + 4.2 X2 + 4.1 X4 + 3.4 X5 + 6.5 X6 + 4.2 X8 <=   1040
        5)   0.8 X1 + 0.4 X2 + 1.1 X3 + 1.1 X4 + 1.9 X5 + 0.8 X6 + 1.2 X7
     + 0.4 X8 <=   260
        6)   X1 =    60
        7)   X2 >=   5
        8)   X3 >=   5
        9)   X4 >=   5
       10)   X5 >=   5
       11)   X6 >=   5
       12)   X7 >=   5
       13)   X8 >=   5
       14)   A2 >=   5
       15)   A3 >=   5
       16)   A4 >=   5
       17)   A5 >=   5
       18)   A6 >=   5
       19)   A7 >=   5
       20)   A8 >=   5
       21)   X2 + A2 =    60
       22)   X3 + A3 =    30
       23)   X4 + A4 =    25
       24)   X5 + A5 =    35
       25)   X6 + A6 =    25
       26)   X7 + A7 =    35
       27)   X8 + A8 =    10
END

:  LP OPTIMUM FOUND AT STEP     15

       OBJECTIVE FUNCTION VALUE

       1)    224.024400

 VARIABLE        VALUE          REDUCED COST
       X1        60.000000          .000000
       X2        55.000000          .000000
       X3         5.000000          .000000
       X4        20.000000          .000000
       X5        30.000000          .000000
       X6        19.024390          .000000
       X7        30.000000          .000000
       X8         5.000000          .000000
```

A2	5.000000	.000000
A3	25.000000	.000000
A4	5.000000	.000000
A5	5.000000	.000000
A6	5.975610	.000000
A7	5.000000	.000000
A8	5.000000	.000000

ROW	SLACK OR SURPLUS	DUAL PRICES
2)	.000000	.243902
3)	135.792700	.000000
4)	210.341500	.000000
5)	52.280490	.000000
6)	.000000	.219512
7)	50.000000	.000000
8)	.000000	-.121951
9)	15.000000	.000000
10)	25.000000	.000000
11)	14.024390	.000000
12)	25.000000	.000000
13)	.000000	.000000
14)	.000000	-.707317
15)	20.000000	.000000
16)	.000000	-.365854
17)	.000000	-.878049
18)	.975610	.000000
19)	.000000	-.073171
20)	.000000	-1.000000
21)	.000000	.707317
22)	.000000	.000000
23)	.000000	.365854
24)	.000000	.878049
25)	.000000	.000000
26)	.000000	.073171
27)	.000000	1.000000

NO. ITERATIONS= 15

DO RANGE(SENSITIVITY) ANALYSIS?
?
RANGES IN WHICH THE BASIS IS UNCHANGED:

OBJ COEFFICIENT RANGES

VARIABLE	CURRENT COEF	ALLOWABLE INCREASE	ALLOWABLE DECREASE
X1	1.000000	INFINITY	INFINITY
X2	1.000000	INFINITY	.707317
X3	1.000000	.121951	INFINITY
X4	1.000000	INFINITY	.365854
X5	1.000000	INFINITY	.878049
X6	1.000000	.078947	.108696
X7	1.000000	INFINITY	.073171
X8	1.000000	INFINITY	1.000000
A2	.000000	.707317	INFINITY
A3	.000000	INFINITY	.121951
A4	.000000	.365854	INFINITY
A5	.000000	.878049	INFINITY
A6	.000000	.108696	.078947
A7	.000000	.073171	INFINITY

APPENDIX F

FIGURE 1: Slack Time per Workcenter

APPENDIX G

Sensitivity Analysis for Selected Technical Coefficients

(LINDO Printouts)

△ C 21

LINDO/PC (9 AUG 89)

: : : ?

:

2 3) 3.364 X1 + 2.8 X2 + 3.2 X5 + 0.3 X6 + 4.5 X8 <= 480

: LP OPTIMUM FOUND AT STEP 16

OBJECTIVE FUNCTION VALUE

1) 224.012100

VARIABLE	VALUE	REDUCED COST
X1	60.000000	.000000
X2	54.982550	.000000
X3	5.000000	.000000
X4	20.000000	.000000
X5	30.000000	.000000
X6	19.029500	.000000
X7	30.000000	.000000
X8	5.000000	.000000
A2	5.017447	.000000
A3	25.000000	.000000
A4	5.000000	.000000
A5	5.000000	.000000
A6	5.970503	.000000
A7	5.000000	.000000
A8	5.000000	.000000

ROW	SLACK OR SURPLUS	DUAL PRICES
2)	.000000	.224820
3)	.000000	.260791
4)	210.381600	.000000
5)	52.283380	.000000
6)	.000000	-.596727
7)	49.982550	.000000
8)	.000000	-.034173
9)	15.000000	.000000
10)	25.000000	.000000
11)	14.029500	.000000
12)	25.000000	.000000
13)	.000000	-.173561
14)	.017448	.000000
15)	20.000000	.000000
16)	.000000	-.415468
17)	.000000	-.053058
18)	.970503	.000000
19)	.000000	-.145683
20)	.000000	.000000
21)	.000000	.000000

22)	.000000	.000000
23)	.000000	.415468
24)	.000000	.053058
25)	.000000	.000000
26)	.000000	.145683
27)	.000000	.000000

NO. ITERATIONS= 16

DO RANGE(SENSITIVITY) ANALYSIS?
? :

Δc_{31}

```
INDO/PC (9 AUG 89)

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 :  : ?  ?  ?  ?  ?  ?  ?  ?  ?  ?  ?  ?  ?  ?  ?  ?  ?  ?  ?  ?  ?  ?  ?  ?

(3)  4)  8.1 X1 + 4.2 X2 + 4.1 X4 + 3.4 X5 + 6.5 X6 + 4.2 X8 <=   1040
:  LP OPTIMUM FOUND AT STEP      16

      OBJECTIVE FUNCTION VALUE

      1)      223.929800

VARIABLE        VALUE          REDUCED COST
      X1        60.000000          .000000
      X2        55.000000          .000000
      X3         5.775921          .000000
      X4        20.000000          .000000
      X5        30.000000          .000000
      X6        18.153840          .000000
      X7        30.000000          .000000
      X8         5.000000          .000000
      A2         5.000000          .000000
      A3        24.224080          .000000
      A4         5.000000          .000000
      A5         5.000000          .000000
      A6         6.846156          .000000
      A7         5.000000          .000000
      A8         5.000000          .000000


     ROW   SLACK OR SURPLUS     DUAL PRICES
      2)          .000000          .217391
      3)       136.053800          .000000
      4)          .000000          .016722
      5)        52.123410          .000000
      6)          .000000          .168896
      7)        50.000000          .000000
      8)          .775921          .000000
      9)        15.000000          .000000
     10)        25.000000          .000000
     11)        13.153840          .000000
     12)        25.000000          .000000
     13)          .000000          .000000
     14)          .000000         -.668896
     15)        19.224080          .000000
     16)          .000000         -.366221
     17)          .000000         -.834448
     18)         1.846156          .000000
     19)          .000000         -.173913
     20)          .000000         -.929766
     21)          .000000          .668896
```

21)	.000000	.673716
22)	.000000	.000000
23)	.000000	.176737
24)	.000000	.000000
25)	.000000	.167674
26)	.000000	.000000
27)	.000000	.800604

NO. ITERATIONS= 19

DO RANGE(SENSITIVITY) ANALYSIS?
? :

DC47 1

LINDO/PC (9 AUG 89)

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: : : ?

:
5) 0.8 X1 + 0.4 X2 + 1.1 X3 + 1.1 X4 + 1.9 X5 + 0.8 X6 + 2.9 X7
+ 0.4 X8 <= 260

: LP OPTIMUM FOUND AT STEP 21

OBJECTIVE FUNCTION VALUE

1) 224.024400

VARIABLE	VALUE	REDUCED COST
X1	60.000000	.000000
X2	55.000000	.000000
X3	5.000000	.000000
X4	20.000000	.000000
X5	30.000000	.000000
X6	19.024390	.000000
X7	30.000000	.000000
X8	5.000000	.000000
A2	5.000000	.000000
A3	25.000000	.000000
A4	5.000000	.000000
A5	5.000000	.000000
A6	5.975610	.000000
A7	5.000000	.000000
A8	5.000000	.000000

ROW	SLACK OR SURPLUS	DUAL PRICES
1 2)	.000000	.243902
2 3)	135.792700	.000000
3 4)	210.341500	.000000
4 5)	1.280484	.000000
6)	.000000	.219512
7)	50.000000	.000000
8)	.000000	-.121951
9)	15.000000	.000000
10)	25.000000	.000000
11)	14.024390	.000000
12)	25.000000	.000000
13)	.000000	.000000
14)	.000000	-.707317
15)	20.000000	.000000
16)	.000000	-.365854
17)	.000000	-.878049
18)	.975610	.000000
19)	.000000	-.073171
20)	.000000	-1.000000

21)	.000000	.707317
22)	.000000	.000000
23)	.000000	.365854
24)	.000000	.878049
25)	.000000	.000000
26)	.000000	.073171
27)	.000000	1.000000

NO. ITERATIONS= 21

DO RANGE(SENSITIVITY) ANALYSIS?
? :

Δc_{47} (2)

LINDO/PC (9 AUG 89)

: : : ?

:

5) 0.8 X1 + 0.4 X2 + 1.1 X3 + 1.1 X4 + 1.9 X5 + 0.8 X6 + 2.95 X7
+ 0.4 X8 <= 260

over limit

: LP OPTIMUM FOUND AT STEP 18

OBJECTIVE FUNCTION VALUE

1) 224.017100

VARIABLE	VALUE	REDUCED COST
X1	60.000000	.000000
X2	55.000000	.000000
X3	5.000000	.000000
X4	20.000000	.000000
X5	30.000000	.000000
X6	19.116510	.000000
X7	29.900610	.000000
X8	5.000000	.000000
A2	5.000000	.000000
A3	25.000000	.000000
A4	5.000000	.000000
A5	5.000000	.000000
A6	5.883489	.000000
A7	5.099394	.000000
A8	5.000000	.000000

ROW	SLACK OR SURPLUS	DUAL PRICES
1 2)	.000000	.237438
2 3)	135.765000	.000000
3 4)	209.742700	.000000
4 5)	.000000	.033131
6)	.000000	.213694
7)	50.000000	.000000
8)	.000000	-.128658
9)	15.000000	.000000
10)	25.000000	.000000
11)	14.116510	.000000
12)	24.900610	.000000
13)	.000000	.000000
14)	.000000	-.701822
15)	20.000000	.000000
16)	.000000	-.346218
17)	.000000	-.818332
18)	.883489	.000000
19)	.099394	.000000
20)	.000000	-.986748

21)	.000000	.701822
22)	.000000	.000000
23)	.000000	.346218
24)	.000000	.818332
25)	.000000	.000000
26)	.000000	.000000
27)	.000000	.986748

NO. ITERATIONS= 18

DO RANGE(SENSITIVITY) ANALYSIS?
? :