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Title: Optimization of an Integrated Circuit Manufacturing Process Using Linear Programming Techniques

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Abstract: This report develops a Linear Programming Model to optimize the integrated circuit manufacturing process relative to business demand. Management must optimize equipment utilization and use excess capacity with opportunistic incremental business. This model is constructed to make a selection from several potential customers based on the specific requirements of the customers and constraints of the equipment for each unique set of deliverables. The model will be valid for use over the next year, and could be utilized by company management in committing to opportunities, and by production scheduling personnel to determine production run quantities.

OPTIMIZATION OF AN INTEGRATED CIRCUIT MANUFACTURING PROCESS USING LINEAR PROGRAMMING TECHNIQUES

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EMP - P9011

Optimization of an Integrated Circuit Manufacturing Process Using Linear Programming Techniques

Good project, but it needs enhancements:
1) A section at the end to summarize & interpret your results
2) Recommendations,
3) Conclusions you can draw

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EXECUTIVE SUMMARY

A problem formulation that often lends itself to solutions using Linear Programming techniques are situations involving scheduling and resource allocations in a manufacturing production process. An integrated circuit manufacturing process using a local company, TriQuint, as a reference for a realistic set of data pertinent to this industry was examined. The problem formulation revolved around making an optimal decision to accept or reject business opportunities presented to the integrated circuit manufacturer, based on constraints of plant capacity. Specifically, while the operating point of the process was below capacity limits, we were attempting to determine what additional business could be accepted to fill the remaining capacity, based on the objective of optimizing incremental profit for our plant.

The steps followed included determination of an objective function, exploring the parameters of the various process steps involved in manufacturing the integrated circuits, and identifying the constraints on that process. Having accomplished this, we utilized a linear programming software package (the LINDO model), and found the optimal solution to our problem. The final step was to perform a sensitivity analysis on the decision variables to gain a better understanding of the relative relationships between the factors in our model, and better knowledge of the magnitude each variable carried in the decision process. The experience is summarized by concurring that the linear programming techniques can be applied successfully to a problem set such as this. Further, linear program modeling is a good tool to help managers sharpen their understanding of relevant issues prior to making a decision or judgement about a specific situation.

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RECOMMENDATION

The use of Linear Programming has provided a better perspective of the business and production environment at TriQuint. This has provided strategies to follow when negotiating product deliveries with key potential clients, enabling TriQuint to maximize profits.

In this case, the TriQuint manufacturing plant does not have the capability to meet the minimum needs of all clients. The preferred alternative is to negotiate the minimum wafer delivery with client X2, Hotrod. The minimum wafer delivery should be 580 wafers instead of 1500 wafers. This would provide a maximum profit of $5,049,725.

Is this the net benefit resulting from your recommend'n?

INTRODUCTION

The primary intent of this project and the model development is to provide optimization of the integrated circuit manufacturing process relative to the available business demand. Management desires to optimize equipment utilization and use excess capacity over and above normal business levels by filling remaining capacity with opportunistic incremental business. The model will be constructed to make a selection from several potential customers based on the specific requirements of the customers and constraints of the equipment for each unique set of deliverables. The model will be valid for use over the next year, and could be utilized by company management in committing to business opportunities, and by production scheduling in determining production run quantities and other variables.

BACKGROUND

Tektronix began Gallium Arsenide (GaAs) research in 1978 in the belief that high speed circuits fabricated from this material would be important to the development of high performance instruments. In 1984, the technology had reached a point that practical circuits could be fabricated.

Tektronix analyzed its internal needs for GaAs technology and the requests for capital, and concluded that the requirements for this technology (by Tektronix) would probably never exceed 5 - 10% of the production capability needed to sustain its business levels. Thus a new firm, TriQuint was set up as a subsidiary of Tektronix, with key employee ownership of up to 10%. TriQuint means III, V (3,5) representative of the fact that the materials gallium and arsenide are from column III and column V of the periodic table. It was anticipated that it would take 4 to 5 years to achieve breakeven in the business, at which time Tektronix would look for corporate partners.

TriQuint is growing at a rate of 50% to 70% per year and is expected to pass through breakeven toward the latter part of 1990. At this point in its corporate development, TriQuint still has surplus capacity, and it is within this context that the linear program in this paper is formulated and analyzed.

TYPE OF MODEL TO BE USED

A matrix model approach to solving this problem was selected, rather than a network or pure mathematical model. The rationale for this choice is that given our problem description, this format seemed to be the most natural fit. The problem does not need the high power or flexibility that the pure mathematical model will provide for our specific problem formulation. See "The Linear Programming Model -- Matrix Model Approach" section for further details.

However, it is useful to note that the network approach offers a good method for describing the process relationships that exist in our case, and we did not want to "force fit" only one type of model to the problem. Consequently, we offer the network approach as an aid to the reader in understanding the complex nature of our project study. See the "Network Approach Overview" section of the paper.

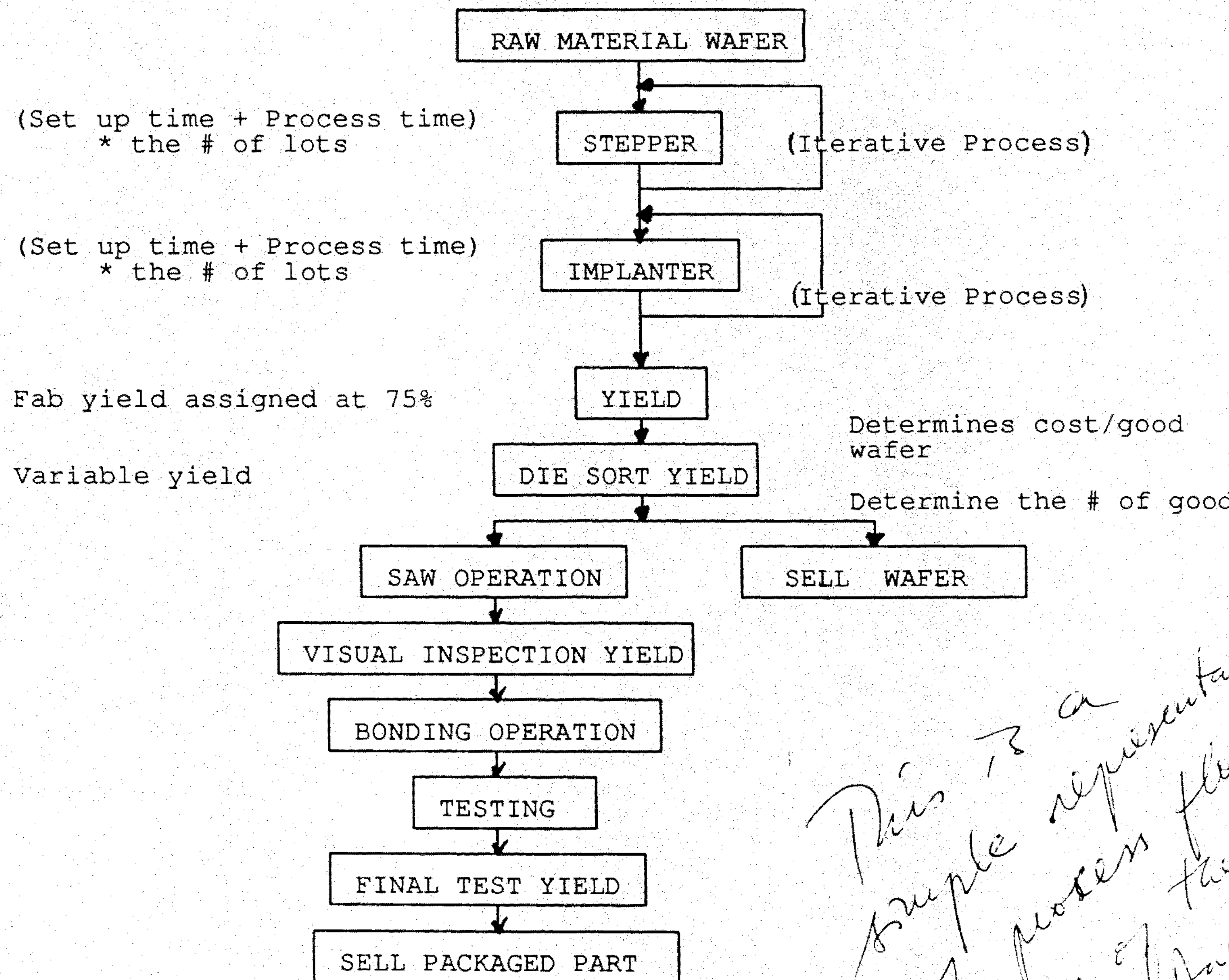
MODEL DEFINITION

The basic problem involves meeting both the capacity needs of the organization (TriQuint) and the customer needs for specific types and quantities of integrated circuits (IC). It is important to find the best "match" between these two requirements in order to meet both end objectives. For example, determining whether to sell an integrated circuit in a wafer format, as single die, or as a packaged component was one consideration which needed to be addressed. Other options included whether the customer would do their own assembly, inspection, and testing or if it would be done within the capacity constraints of the facility.

MANUFACTURING PROCESS

The TriQuint production facility makes Gallium Arsenide high speed circuits. An overview of the manufacturing process includes procurement of the appropriate raw material, performing circuit imaging through photolithography, and doping the wafers with an "implanter". Depending upon customer requirements, the wafers would be inspected, sawed into individual die, sorted, and tested. At this point the die could either be sold to the customer (in die form), or bonded into a leadframe and packaged as an electronic

NETWORK ANALYSIS MODEL



This is a simple representation of process flow. The use of the term "Network Analysis Model" is misleading.

component prior to being sold to the end user. Figure 1 is a Network Analysis Model graphically showing the sequence of steps occurring in the manufacturing process.

The facility has machine and labor limitations which limit the production capability of the plant. These limitations are:

1. There are 3900 hours available on the **stepper** machine.
2. There are 1950 hours available on the **implanter** machine.
3. There are 1950 hours available on the **bonder** machine.
4. There are 27,500 labor hours available for the "**assembly**" process.

The average labor rate that will be used for the manufacturing process staff will be $15.00 per hour.

POTENTIAL CLIENT BASE

The objective of the model is to determine the optimum use of the manufacturing facilities based on the business opportunities available. Four potential clients with varying needs were reviewed. These will be called Micro Circuit, Hotrod, Lightning, and Standard Jobs.

Micro Circuit requires a minimum of 100 wafers to satisfy their production needs. They are willing to accept up to 150 wafers. They also desire TriQuint to saw the wafers and provide packaging for the finished micro circuit.

Hotrod required a minimum of 1500 wafers to satisfy their needs, but are willing to take up to 2000 wafers. Packaging of the product is not required. The wafer will be delivered direct to Hotrod.

Lightning requires a minimum of 600 wafers to satisfy their needs, but are willing to take up to 900 wafers. Packaging of the product is not required. The wafer will be delivered directly to Lightning.

The final client in the potential client base is called Standard Jobs. This is the name that will be given to special order projects. No minimum number of wafers is required, but a maximum of 200 wafers will be assumed.

Manufacturing information for each of the four clients was gathered. The information is summarized in Table 1. Note that this information is not actual operating information of TriQuint. The actual costs are proprietary. These costs resemble values that are typical in the high tech manufacturing industry and are acceptable for this exercise.

TABLE 1
TRIQUINT CLIENT DATA

	Micro-C (X1)	Hotrod (X2)	Lightning (X3)	Std. Jobs (X4)
Wafer Size	3"	4"	4"	3"
Lot Size	8	16	16	4
Photo Steps	12	14	14	12
Implant Steps	4	5	8	4
Die Sites	1200	160	160	NA
Die Sort Yield	80%	75%	75%	NA
Bonder (Hrs/die)	0.00	0.005	0.005	NA
Assembly (Hrs/die)	0.02	0.08	0.05	NA
Test Yield	90%	NA	NA	NA
Package Cost	$3.00	NA	NA	NA
Package Price	$14.00	$8.00	$5.00	NA
Wafer Price	NA	$1,870	$2,370	$7,000
Product Price	$9,677	$2,638	$2,850	$7,000
Wafer Orders	150	2000	900	200
Min. Order Size	100	1500	600	NA
Inc. Cost	$1,110	$1,081	$1,039	$845
Inc. Revenue	$8,566	$1,557	$1,811	$6,155

MODEL DEVELOPMENT

The intent of this problem solution is to determine the combination of clients and their production needs that will maximize TriQuint's profits. This must be performed using the plant's existing process capability. A linear model for examination of this manufacturing problem was developed.

DETERMINATION OF OBJECTIVE FUNCTION

The objective function for the model will be to maximize profits. To determine this function, the Incremental Revenue for each of the four components was determined. The Incremental Revenue was calculated on a cost per wafer basis. The Incremental revenue is determined by the following equation:

Incremental Revenue = Product Price - Incremental Cost

The Product Price is the value at which each wafer is sold to the client. The final product can be in the form of a wafer or completely packaged. The product can also be supplied with or without testing. The amount of service provided determines the package price. This price is calculated by taking the wafer price or the package's yield per wafer and multiplying by the package price.

The Incremental Cost was determined by calculation. Factors such as materials cost, process steps, labor cost, and process efficiency were considered in this calculation.

Table 2 summarizes the cost information that was calculated for each client. From this information, the objective function was determined to be:

$$\text{MAX} \quad 8566\,X1 + 1557\,X2 + 1811\,X3 + 6155\,X4$$

Where X1 is Micro Circuit, X2 is Hotrod, X3 is Lightning, and X4 is Standard Jobs.

DETERMINATION OF RIGID CONSTRAINTS

The constraints for a manufacturing process are the limitations in the acquisition of raw materials, available labor, process limitations, and client needs. For this model, acquisition of raw materials was not a limitation. The limitations used were steps in the process (stepper, implanter, bonder) and labor.

TABLE 2
WAFER COST SUMMARY

	Converted Wafer Price	Incremental Cost	Incremental Revenue
Micro Circuits	$9677	1110	$8566
Hotrod	2638	1081	1557
Lightning	2850	1039	1811
Standard Jobs	7000	845	6155

Manufacturing Process Limitations

The stepper process has a given limitation of 3900 hours. The requirements of the stepper were determined for each client. The stepper hours were determined using the following equation:

$$\text{Stepper Hrs.} = \frac{(\text{Setup Time})(\text{No. Photo Steps}) + (\text{Lot Size})(\text{no. Photo Steps})(\text{Process Time})}{(\text{Lot Size})(\%\text{Fab Yield})}$$

The implanter process has a given limitation of 1950 hours. The requirements of the implanter were determined for each client. The implanter hours were determined using the following equation:

$$\text{Implanter Hrs.} = \frac{\text{(Setup Time)(No. Implanter Steps)} + \text{(Lot Size)(No. Implanter Steps)(Process Time)}}{\text{(Lot Size)(\%Fab Yield)}}$$

The bonder process has a given limitation of 1950 hours. The requirements of the bonder were determined for each client. The bonder hours were determined using the following equation:

$$\text{Bonder Hrs.} = \text{(Die Sites)(Die Sort yield)(VI Inspect Yield)(Bonder Hrs)}$$

The final manufacturing limitation that was considered is the number of labor hours available. The labor hours required for each client was determined using the following equation:

$$\text{Labor Hrs.} = \text{(Stepper hrs)} + \text{(Implanter Hrs)} + \text{(Sawing Hrs)} + \text{(Die sort Hrs)} + \text{(VI Hrs)} + \text{(Assembly Hrs)}$$

The results of these calculations for each of the clients is displayed in Table 3.

TABLE 3
MANUFACTURING PROCESS LIMITATIONS

	Micro-C (X1)	Hotrod (X2)	Lightning (X3)	Std. Jobs (X4)
Stepper Hours	2.1	1.8	1.8	4.6
Implanter Hours	0.5	0.6	0.9	0.8
Bonder Hours	2.3	0.5	0.5	-
Labor Hours	37.0	13.1	10.5	5.4

Client Requirements

Each of the four clients has given specific required quantities of wafers to TriQuint. These quantities were shown on Table 1 with the manufacturing data for each client. Both the upper bound and lowers bound for each client is used as a separate constraint.

Variable Limitations

The final set of constraints applied to the model was to limit each variable to a positive integer. This insures that the solution must be positive as required by the Simplex Method.

The variables used in the model are actually integer variables because partial wafers cannot be sold. Since the size of the variables are relatively large, with the smallest one at 100, it was assumed that continuous variables could be used. This provided the benefit of being able to use the LINDO program to perform a sensitivity analysis. An analysis using integer variables to confirm this assumption is in Appendix C.

LINEAR MODEL

The linear model was developed using the objective function and rigid constraints developed above. The completed model is shown in Figure 2.

The linear model was evaluated using the microcomputer based software program LINDO (Linear, INteractive, and Discrete Optimizer). LINDO is a command oriented program for the evaluation of simple linear models using the Simplex Method. LINDO provides the tools to determine the feasibility of the model as well as perform a sensitivity analysis on the model.

FIGURE 2
LINEAR MODEL

```
MAX    8566 X1 + 1557 X2 + 1811 X3 + 6155 X4
SUBJECT TO
      2)  2.1 X1 + 1.8 X2 + 1.8 X3 + 4.6 X4 <=  3900
      3)  0.5 X1 + 0.6 X2 + 0.9 X3 + 0.8 X4 <=  1950
      4)  37 X1 + 13.1 X2 + 10.5 X3 + 5.4 X4 <=  27500
      5)  2.3 X1 + 0.5 X2 + 0.5 X3 <=  1950
      6)  X1 >=  100
      7)  X2 >=  1500
      8)  X3 >=  600
      9)  X1 <=  150
     10)  X2 <=  2000
     11)  X3 <=  900
     12)  X4 <=  200
     13)  X1 >=  0
     14)  X2 >=  0
     15)  X3 >=  0
     16)  X4 >=  0
END
```

constraint 7 specifying X2 > 1500

MODEL RESULTS

The TriQuint manufacturing linear model was ~~evaluated~~ Solved using LINDO. The solution to this model is infeasible showing that the ~~restraint X2~~ cannot be met. ~~The restraint for X2 was ≥ 1500.~~ The model solution showed that the maximum value that X2 could be was 1335. The value of the objective function was $4,023,162. The output for this LINDO run can be found in Appendix A: Original Model LINDO Output.

This infeasible solution means that there is not enough capability in the present plant to meet the minimum demands for each of the four clients. The optimum production scheme determined by the present model is to provide 100 wafers to Micro Circuit, 1335 wafers to Hotrod, and 600 wafers to Lightning. No wafers would be supplied to Standard Jobs. This scenario would produce a profit for TriQuint of $4,023,162.

PROFIT ANALYSIS

The original model run was infeasible with the limitation being the wafer requirements for client X2. Various modifications were made to the model to analyze the allocation of manufacturing resources to satisfy the various client wafer production requirements. A summary of these models is shown in Table 4. The listings for each of the model runs can be found in Appendix B: Profit Analysis.

As shown in Table 4, the maximum income (objective function) for TriQuint would be to limit the number of wafers deliverable to Hotrod, client X2. Providing the maximum number of wafers desired by the other three clients and negotiating with Hotrod to deliver only 580 wafers would maximize profits for TriQuint. This would produce an income of $5,049,725.

The alternative of reducing by 10% the minimum required by all four clients was reviewed in analysis number six. this did not provide a good solution. The objective function was slightly higher at $4,339,667, with two of the four clients getting less than they desired.

The final step to this analysis was to increase the production limits in the manufacturing process so that the maximum requirements for each client could be met. This analysis demonstrated the total potential income of the four clients if TriQuint could meet their orders. This analysis, LPMAX, showed a maximum income of $7,259,800. To meet the production needs to realize this income, TriQuint would need to increase their stepper time by 65% to 6455 hours, their implanter time by 15% to 2246 hours, and their labor hours by 54% to 42,281 hours. The bonder hours would go unchanged as the minimum needed is 1795 hours or 92% of its present capacity. This calculation could also have been done by placing the maximum wafer deliveries for each client into the objective function. When this is done, the same maximum income of $7,259,800 is calculated.

SENSITIVITY ANALYSIS

The sensitivity analysis has been divided into three parts. The are the supply-demand analysis, profitability analysis, and resource availability analysis. It has been assumed that the technological coefficients are valid for the manufacturing/implementation time frame that this model will be used. For this reason, a sensitivity analysis for the technological coefficients was not performed.

TABLE 4
PROFIT ANALYSIS SUMMARY

ANALYSIS NO	FILE NAME	FEASIBILITY STATUS	OBJECTIVE VALUE	VARIABLES X1	X2	X3	X4
	LPIN	INFEASIBLE	$4,023,162	100	1335	600	0
1	LPX1	FEASIBLE	$3,810,919	40	1500	600	6
2	LPX2	FEASIBLE	$4,034,902	100	1335	600	2
3	LPX21	FEASIBLE	$5,049,725	150	580	900	200
4	LPX3	FEASIBLE	$4,804,569	150	1500	0	192
5	LPXX	FEASIBLE	$5,049,725	150	580	900	200
6	LPX90	FEASIBLE	$4,339,667	103	1350	540	61
7	LPX1P90	INFEASIBLE	$3,780,946	41	1500	600	0
8	LPX2P90	INFEASIBLE	$4,002,320	95	1350	600	0
9	LPX3P90	INFEASIBLE	$3,989,381	59	1500	540	0
10	LPMAX	FEASIBLE	$7,259,800	150	2000	900	200

The first approach was to match the current excess capacity with the possible business opportunity based on the maximization of the incremental revenue (profitability). Several alternatives were developed. Adjustments to the model were made to take the infeasible solution to an alternative that would give maximum incremental profit for the company.

Based on the profitability analysis, the alternative which provides the maximum incremental profit for the current profitability and resources is Analysis Number 3 as shown on Table 4. The sensitivity analysis will be based on this alternative where the minimum order required for client X2 (Hotrod) was relaxed.

SENSITIVITY ANALYSIS OF SUPPLY-DEMAND

A sensitivity analysis performed on the right hand side values was performed. The results are shown on Table 5.

TABLE 5
SENSITIVITY ANALYSIS
RIGHT HAND SIDE VALUES
MINIMUM SUPPLY ORDER

VAR	CUSTOMER	CURRENT RHS. (wafer)	ALLOWABLE INCREASE	ALLOWABLE DECREASE
X1	Micro circuit	100	50 (50%)	Infinity
X2	Hotrod	0	581	Infinity
X3	Lighting	600	300 (50%)	Infinity

A decrease in the minimum order will have no change in the product that is selected. When increasing the minimum order, there are limitation. Within this range, the optimality of the solution will not be changed even though there may be changes in the number of wafers produced. Beyond this range, another optimum solution needs to be found. An analysis was performed on market demand with the results shown in Table 6.

TABLE 6
SENSITIVITY ANALYSIS
MAXIMUM MARKET DEMAND

VAR	CUSTOMER	CURRENT RHS. (wafer)	ALLOWABLE INCREASE	ALLOWABLE DECREASE
X1	Micro circuit	150	176 (117%)	50 (33%)
X2	Hotrod	2000	Infinity	1419 (71%)
X3	Lighting	900	581 (65%)	300 (33%)
X4	Standard Job	200	227 (114%)	136 (68%)

The changes in market demand within this range will not change the optimality of the product chosen, although there can be a change in the values of production and profit.

The increase of X3 (Lighting) product is relatively more sensitive than the other products. If the Lighting demand increases beyond 1481 wafers, the current solution will no longer optimal and we have to find another optimal solution.

For decreases in the market demand, both X1 and X3 are more sensitive than the others. If the decrease in market demand was greater than 33%, then another optimum solution would need to be found.

SENSITIVITY ANALYSIS OF PROFITABILITY

A sensitivity analysis of the objective coefficient was performed. The results are shown on Table 7.

TABLE 7
SENSITIVITY ANALYSIS
PROFITABILITY

VAR	CUSTOMER	CURRENT COEF. ($)	ALLOWABLE INCREASE	ALLOWABLE DECREASE
X1	Micro circuit	8566	Infinity	6750 (79%)
X2	Hotrod	1557	254 (16%)	1557(100%)
X3	Lighting	1811	Infinity	254 (14%)
X4	Standard Job	6155	Infinity	2716 (44%)

If the objective coefficient for each variable changes within the range of allowable increase and decrease, the optimal value of the decision variable will not change. The optimal solution will be given for that situation although the result of the objective will be change.

Table 7 shows that a 16% increase in the profitability (incremental revenue) of the X2 product (Hotrod), and a 14% decrease in the profitability of X3 product (Lighting) would occur. These two products are the most sensitive. More attention should be given to these coefficients, since a change beyond the allowable range will not give the optimal solution or even be feasible. In this case, another optimal solution should be found.

An increase in the profitability of X2 product (Hotrod) above $1811 per wafer equivalent will make this product have a better profitability than the other product(s). The production of other product(s) should be reduced to free some resources for producing this product which is relatively more profitable.

A decrease in the profitability of X3 product (Lighting) below $1557 will lower the profitability of this product. It would be better to reduce the production of this product to free resources for other more profitable products.

SENSITIVITY ANALYSIS OF RESOURCES

A sensitivity analysis on the Right Hand Side values of the resource constraints was performed. The results are shown on Table 8.

TABLE 8
SENSITIVITY ANALYSIS
RIGHT HAND SIDE VALUES
RESOURCE CONSTRAINTS

Row	Resource	CURRENT COEF.	ALLOWABLE INCREASE	ALLOWABLE DECREASE
2	Stepper Hour	3900	524 (13%)	1045 (27%)
3	Implanter Hour	1950	Infinity	557 (29%)
4	Labor Hour	27500	Infinity	3815 (14%)
5	Bonder Hour	1950	Infinity	865 (44%)

The change in resources within the allowable range will not change the decision of the chosen product, although it will change the number of wafers produced and the profit.

Table 7 shows that a 14% decrease in Labor Hours and a 13% increase in Stepper Hours are the most sensitive resources to the decision of the product choice.

An increase in Stepper Hours up to 4424 hours will increase the production of products and profit. Beyond this value, there will be no effect unless accompanied by improvement in other resources.

A decrease in Labor Hours down to 23,685 hours will not change the decision of the selected product. If decreased lower than this value, there will be a change in the decision of the product to produce.