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Abstract: SEC, a manufacturer of silicon and epitaxial wafers faced a problem of allocating equipment and labor resources to maximize profits while meeting product mix requirements. This project developed a linear programming model for the problem. The solution revealed that 5" wafers were least profitable, addition of reactors for 6" wafers was desirable and more efficient use of labor was warranted.

SEC - MANUFACTURING OPTIMIZATION

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EMGT 540 - TERM PROJECT
SEC - MANUFACTURING OPTIMIZATION

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ABSTRACT

SEC, a manufacturer of silicon and epitaxial wafers faced a problem of allocating equipment and labor resources to maximize profits while meeting product mix requirements. After extensive work to develop a linear programming model for the LINDO software, our solution revealed that 5" wafers were least profitable, addition of reactors for 6" wafers was desirable and more efficient use of labor was warranted. These recommendations were in line with current company goals. Better model formulation to account for materials and resource uncertainties and shop floor control for schedule and machine queue optimization are suggested as possible extensions to this project.

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EXECUTIVE SUMMARY

SEC is a manufacturer of raw material used in the production of integrated circuits. SEC produces silicon wafers ranging in diameter from 4" to 6" with a total of 6 different product types. Shared equipment and labor resources are used for the product. The main objective of this project was to develop a model to optimize productivity through proper allocation of equipment and labor in order to maximize profit. Additionally, it was also desired to run a sensitivity analysis to determine if current marketing policies and plans for adding equipment capacity were in keeping with the company goals.

Literature search revealed that such problems have been solved using linear programming (LP). Three methods of optimization were found. They are constant demand production, schedule optimization and strategic mix optimization (which attempts to deal with multiple conflicting objectives). Such problems lead to 'demand to manufacturing system' analyses or 'Just in Time' systems and job scheduling problems. The specific model developed for the SEC problem consisted of an objective function based on the price and cost of each wafer type and a series of constraints based on equipment capacity, labor rate for each lot or individual units of each product and additional requirements for maintenance and administration.

Analysis of the initial LINDO* run revealed discrepancies in terms of labor usage and total production with respect to actual production. These findings were utilized to make corrections to the original model. Sensitivity analysis of the second LINDO run clearly showed that 5" wafers were least profitable for the company. Additionally large dual prices for reactor capacity constraints and the final LINDO run proved that the addition of more efficient reactors capable of producing 6" wafers would make a substantial increase in the objective function. Both of these conclusions are in accordance with the company's current policy.

The solution of the model indicates that labor is being used at 66% of capacity and that the wafer production should be 30% higher than actual production even after additional corrections. This is due to the interdependence of processes, actual availability of labor, labor efficiency, set up times, starting material inventory, and scheduling of the processes to minimize dwell time.

From the analysis of results a number of extensions to the current problem seem possible. Since cross training of personnel will increase flexibility of labor, it can be studied as a factor in solving this as a shop floor control problem. Considerable uncertainty exists in labor usage at SEC. Employee breaks, downtime, setup times, and inventory optimization can be studied in reducing this uncertainty and improving overall process management. Equipment reliability optimization is yet another approach for obtaining a solution.

In conclusion, performing a linear programming optimization for the SEC manufacturing model resulted in a better understanding of the equipment constraints, labor utilization, and product mix which should result in an improved manufacturing and marketing strategy for the company.

* -- LINDO (Linear, INteractive, Discrete Optimizer) is linear programming software produced by Linus Schrage, Graduate School of Business, University of Chicago, The Scientific Press, San Francisco, CA, Copyright 1991.

INTRODUCTION

The goal of this project is to model and optimize a manufacturing process for productivity and profit through proper allocation of equipment and personnel resources. The primary measurements will be production throughput and overall profit. The secondary goal will be a sensitivity analysis to determine which products should receive the most marketing focus and which equipment and personnel resources are most critical.

SEC manufactures bare silicon wafers and epitaxial coated wafers used in the manufacture of integrated circuits. This project is focused on the epitaxial manufacturing operation. SEC produces six major epi products. The manufacturing operation has eight sequential steps (see figure 1). Each of the products requires different proportions of equipment and personnel. Process yield and product cost information is described in "generic" terms with specific numbers normalized.

The product mix consists of three different wafer sizes (4", 5" & 6") with additional process variations for 4" and 5" wafers. Each wafer size/process requires a different reactor configuration. There are three different types of epitaxial deposition reactors. Type "A" and "B" reactors can not process 6" wafers. Type "C" reactors can not process 4" wafers. Furthermore, not all processes can be run on all the reactors. The number of reactors and size/process capabilities are summarized in the model description. Maximum usage of this equipment, with a minimum of set-up changes is assumed to be critical.

Scheduling for the manufacturing area is done on a weekly basis, with just-in-time manufacturing techniques. Product mix is determined by individual customer orders. The manufacturing operation is based on 24 hours per day, seven days per week. This eliminates some of the normal lost production time for equipment start-up at the first of the week and the subsequent shut-down at the end of the week or shift.

Epitaxy is one of the oldest and most important technologies in the fabrication of semiconductor devices. Epi is used in IC fabrication for many reasons [Zee]:

1) Epi increases speed for analog devices.
2) Epi increases current carrying capability for power bipolar devices.
3) Epi improves speed and performance in computer logic and memory devices.
4) Epi eliminates "latch-up" in CMOS devices.
5) Epi improves immunity to noise in MOS devices.

Epi is a shortened form of the word "epitaxy". Epitaxy is a transliteration of two Greek words - "epi", meaning "upon" and "taxis", meaning "ordered". The term epitaxy is typically applied to processes used to grow a thin crystalline layer (0.5 to 20 microns) on a crystalline substrate. Silicon epitaxy literally means silicon atoms ordered upon other silicon atoms. In the epitaxial process, the single crystal substrate serves as the seed crystal for the epitaxial layer [O'Ferrell].

The silicon epi layer is used to improve the performance of bipolar transistors and bipolar integrated circuits. By growing a lightly doped epitaxial layer over a heavily doped silicon wafer, the bipolar device can be optimized for various electrical characteristics. One key characteristic is high breakdown voltage of the collector-substrate junction, while maintaining low collector resistance. This low collector resistance provides high device operating speeds at moderate electrical currents [Wolf].

Complementary Metal Oxide Semiconductor (CMOS) is the most widely used of any of the IC fabrication sequences. Leading microprocessors, application specific IC's (ASIC's), and dynamic random access memories (DRAM's) larger than 1 Mbit are almost exclusively constructed using CMOS technology. The starting substrate for CMOS device designs is typically P-type silicon with a relatively thick epi layer; CMOS devices are fabricated totally within the epitaxial layer.

LITERATURE SEARCH

A literature search was performed to facilitate a better understanding of modeling and optimizing manufacturing processes for productivity and profit. Three basic approaches were found. Optimize production given fixed equipment and personnel resources. Optimize the process schedule given fixed equipment, personnel resources, and time constraints. Develop a strategic mix of scheduling and resource allocation to optimize the production process.

Resource Optimization

Resource optimization is perhaps the most straightforward and common approach to optimizing a manufacturing plant. Typically, a manufacturing plant produces several products using generic equipment and cross-trained personnel. It is assumed that products are in demand and can be sold for a profit. Several examples of resource optimization were found in the literature.

An excellent starting source of examples of simple resource optimization are found in linear programming textbooks and software manuals. In an introduction to mathematical programming textbook, Winston starts from the basics to develop the optimization methodology [Winston]. Schrage outlines several resource optimization examples in an introduction to the LINDO linear programming software [Schrage]. Both textbooks are applications oriented; however, the examples are generic in nature. To this end, journal and trade magazines provide a more practical source of optimization methods using linear programming.

Linear programming-based production planning of a job-shop manufacturing system is detailed by Proth and Xie [Proth]. They use the objective function to optimize profit given inventory and backlog costs. The optimum part configuration is determined to balance resource loading and to optimize the use of the tools available. Li uses linear programming for planning material flows in open-pit mining to optimize profits [Li]. Interestingly, the least mean square of intertruck-time deviation is the criterion for optimally matching trucks with shovels. These methods seem most practical to the SEC manufacturing problem.

Similarly, Chow uses linear programming to minimize the sum of inventory and backlog subject to a set of resource constraints for a planning window [Chow]. Bahl et. al. successfully apply linear programming to the product-mix problem inherent in material requirement planning [Bahl]. Voudouris and Grossmann show that many nonlinear models for batch sizes can be reformulated as mixed-integer linear programs [Voudodris]. They considered optimizing multiproduct plants and multipurpose plants with multiple production routes. Their work shows that global optimum solutions are generally guaranteed.

Karthikeyan and Kirishnaswamy apply manpower allocation to production facilities and show this class of problems to be solvable by linear programming [Karthikeyan]. Their solution process involves identifying skill-based component inventories. The inventories relate personnel to equipment to find optimal manpower allocations. Finally, Khorramshahgol and Okoruwa apply linear goal programming to allocating funds for shopping mall leases [Khorramshahgol]. They used a linear goal programming model to optimize profitability given a sales volume, patronization rate, income of shoppers, and the drawing power of anchor tenants. Results indicate that combining a method to forecast patronization rates with a multiple objective resource allocation optimization leads to a satisfactory distribution of lease funds. Such approaches may be useful in determining if additional equipment is justified for SEC manufacturing.

Schedule Optimization

Schedule optimization is more complex than resource optimization. In schedule optimization, each part or group of parts (batch) must be considered independently. The part or batch must be made-to-order by the manufacturing resources to meet a deadline, or the corollary, to find a deadline. Many authors classify this as an "n-part on m-machine" problem. This paradigm is less applicable for SEC manufacturing because of the relatively constant market demand, i.e., products are not made-to-order. Nonetheless, a brief discussion is warranted because most manufacturing plants require some form of materials resource planning.

Panwalker and Rajagopalan discuss how to find optimal processing times and sequences which minimize a cost function containing earliness cost, tardiness cost, and total processing cost for a single-machine sequencing problem where job processing times are controllable variables subject to linear costs and all jobs have a common due date [Panwalker2]. Cheng determines optimal due-dates and sequencing of n jobs on the single-machine where each job is given a constant flow allowance and job earliness and tardiness values [Cheng2]. A linear program derives the optimal constant flow allowance via dual method. Cheng shows that the due-date is independent of job sequences. Additionally, Gupta et. al. show that constant flow allowance, slack time, and total work -based linear programming methods yield equivalent results for determining the optimal sequence and the corresponding optimal due dates for a single-machine flexible machining center [Gupta].

In an N-job one machine sequencing problem, Bector et. al. minimize a penalty function by determining optimal sequences and due dates [Bector1] [Bector2]. Their penalty function is based on the earliness or lateness of jobs given linear per unit costs. Common due dates are found in linear goal programs. They use sensitivity analysis to determine the optimal due date; the corresponding optimal sequence is then developed. Likewise, Liao and You present an integer programming model developed to formulate a general n-job, m-machine job-shop problem using lower and upper bound variables [Liao]. Their approach reduces the number of functional constraints and significantly reduces the computation time for solving the integer model.

In a paper by Hackman and Leachman, thousands of concurrent activities, which are subject to precedence constraints and limitations of resources, are optimized using linear programming [Hackman]. The example of a naval shipyard is used to detail management's strategic objectives for production and utilization of skilled labor and equipment resources via linear equality approximations. Milestone dates are determined through optimization. The authors show that the data structure can be manipulated easily and quickly.

Dar-El et. al. describes a two-tier linear program of master production level and operational level scheduling [Dar-El]. The master production level is scheduled to meet the production forecast and capacity constraints. The operational level uses multi-resource allocation. In practice, the authors show that lead times are reduced by about a third and overtime is lower than previously non-scheduled practices.

Chen and Moricz discuss an approach to scheduling iterative tasks under resource constraints as an integer linear program which minimizes the total execution time [Chen]. Their experimental results show optimal solutions for all the test cases. Likewise, Ronen and Rozen present a generic make-to-order and make-to-stock strategic master production scheduling model [Ronen]. Their model also incorporates utility theory, analytical hierarchy processes, and the de novo programming method. Their work suggests that the SEC manufacturing problem is simple enough to be solved using straightforward linear programming.

Finally, the inspirational paper by Bixby et. al. discusses their experience with solving a 12,753,313 variable linear program for airline crew scheduling on a CRAY Y-MP computer [Bixby]. The problem was decomposed into smaller subproblems and the solution was obtained using simplex method implemented in CPLEX, using an interior point method implemented in OB1, and using a hybrid interior point/simplex approach. Their results show that interior point/simplex combination is best for solving very large-scale linear programs. The SEC manufacturing problem is certainly not as large as Bixby's, yet confidence in the simplex method is gained.

Strategic-Mix Optimization

Most real-life scheduling problems, as noted by Panwalkar et. al., entail multiple objectives that are often in conflict and subject to uncertainty [Panwalker1]. Two of the most common scheduling objectives involve minimizing the mean completion time and minimizing the mean waiting time at any machine. A strategic-mix must be formulated to manage these optimization objectives. Beyond goal programming, bicriterion scheduling is one method of considering both job completion and waiting times.

In a paper by Bagchi, both the mean and variance in wait times for a single nonpreemptive production machine are optimized [Bagchi]. The measure of variation is the sum of absolute pairwise differences. The total scheduling cost is a linear function of the mean and variation of completion times. Bagchi also shows that job waiting times can be substituted for job completion times. Bector et. al. use linear programming to optimize an n job one machine sequencing problem given an objective function that rates the system on the position in the schedule in which the jobs appear [Bector3]. All jobs have a common due date, so unequal job penalties occur when a job is completed before or after its due date. This method determines an optimal sequence that yields the global minimum penalty. The authors say that this is equivalent to minimizing the weighted mean of absolute deviations of completion times from the common due date. Further, the sequence that minimizes the global penalty is V-shaped, i.e., the processing times of jobs are in non-increasing order.

Gagnon and Krasner developed a mixed integer linear programming model that determines the optimal strategic mix of internal and external engineers and equipment to acquire a new technology [Gagon]. Their model accommodates multilevel engineers and equipment with differing performance, control policies, and horizons. Their model helps the manager to recognize the numerous factors and costs to be considered, shows optimal costs, aids in finding various alternative strategies, assesses the effects of different personnel and equipment performance, and finds additional costs by sensitivity analyses on capacity requirements, resource performance, and costs. Such a model may be applicable in determining new employee resources at SEC manufacturing; however, the complexity of the solution process is beyond the scope of a one term project. Akella et. al. discuss part dispatch decisions in electronic test systems with random yield [Akella2]. The problem is to determine how many jobs can be dispatched to each (test) machine given random elimination of jobs. These quantities, in turn, are constrained by capacity. A linear program is developed to minimize the sum of inventory holding, backlogging, and overtime costs. Their work results in a linear decision rule for "myopic" resource allocation, and demonstrates the overall superiority of linear programming. Further, Touran states that nonstationary cycle times have a major impact on production, and linear programming methods are unable to optimize such systems [Touran]. Tourin defines a nonstationary cycle time as a process time that varies with the passage of time. An example is a construction operation where the "haul time" of earth-moving equipment increases as a project progresses. Fortunately, the fabrication processes at SEC manufacturing do not vary over time, and linear programming may be used.

MODEL

A linear programming (LP) model was developed for the SEC manufacturing process. The model is based on the generalized process flow diagram illustrated in Figure 1. The company has over 50 products even though only six major products are shown. The minor products have been generalized into the product groupings as shown in the model. The primary objective is to maximize profit, so the objective function is expressed in terms of revenue minus fixed and variable costs. The generalized revenues and costs for each of the product groupings are also shown in Figure 1.

The objective function is subject to three types of constraints. The first set of constraints expresses the lower bounds on each of the various products. A lower bound is a minimum quantity that must be made. The second set of constraints describes the equipment limitations at each of the operations. The equipment limitations comprise the maximum capacity for each piece of equipment. The third set of constraints deals with personnel limitations at each of the operations such as maximum productivity for an operator at each operation. The appendix contains the model verbally expressed and in equation format (for LINDO solution).

Many assumptions were made in the course of developing and using the model. Assumptions were made concerning additivity, divisibility, certainty, discount, demand, inventory, and supply.

The additivity assumption states that the contribution to the objective function for any variable is independent of the values of the other decision variables. This is generally true. However, there are certain "families" of products that are generally built together; if one is made, the other must be made (or the first is worthless). These products generally represent a very small portion of the total production volume and will be neglected.

The divisibility assumption states that each variable is allowed to assume fractional values. This is certainly true of the variables associated with equipment and personnel hours. Production volume variables are expressed in integer units (whole wafers). However, volumes are large enough to neglect fractional values and accept the divisibility assumtion.

The certainty assumption says that the coefficients of the objective function, the technological variables, and the right hand side values are known with certainty. Although many, or all, of these values change with time, it was assumed that the values were constant for the duration of the product.

The discount and demand assumptions state that there will be no volume discounts or price negotiations and there are no upper bounds on demand. Typically, most prices are negotiated (with volume discounts a large part of the negotiation). However, once prices are fixed, they remain fairly constant for the life of the product. There are certain upper bounds on demand, but SEC's market share is small enough to neglect this restriction.

The inventory and supply assumptions state that inventory costs are negligible and that there is no limitation on raw materials and supply parts. In reality, inventory costs are not negligible; they are included as part of fixed cost. Inventory is minimized by operating according to a Just-In-Time (JIT) philosophy. However, a tenant of the JIT philosophy is to limit raw materials inventory. Inventory levels are statistically calculated to minimize inventory cost and minimize lost revenue due to lack of raw materials.

Note: Model equations are shown below. Transformed LINDO equations are shown in the Appendix along with the rest of the listing.

Figure 1.

Process Flow	Product 4"Std	5"Std	6"Std	4"SR	5"SR	5"NC
Lot Form						
Deposition						
Evaluation						
Laser Mark	No	No	No			No
Removal	No	No	No			No
Final Clean						No
Final Inspection						
Merge Lot						

#Units Produced	X1	X2	X3	X4	X5	X6
Normalized Revenue/Unit	0.44	0.69	1.00	0.50	0.80	0.69
Normalized Variable Cost/Unit	0.25	0.42	0.58	0.32	0.47	0.38
Normalized Fixed Cost	1500					
Minimum Production Qty (Units)	100	300	200	100	100	0

One Week Basis

Constraints

The Objective Function:

1) Maximize Profit = Revenue - Fixed Cost - Variable Cost

The Product Constraints:

1) 4" Standard > 100 units/wk
2) 5" Standard > 300 units/wk
3) 6" Standard > 200 units/wk
4) 4" Removal > 100 units/wk
5) 5" Removal > 100 units/wk
6) 5" NC > 0 units/wk

The Equipment Constraints:

1) #Hours per week = 168
2) No equipment limitations at Lot Form or Final Inspection
3) Throughput at Deposition:

				#Units/lot		
Reactor	#Ea	Throughput	Processes	4"	5"	6"
Type A	2	0.75 lots/hr	X1,X2,X4,X5	21	11	N/A
Type B	2	0.75 lots/hr	X1,X2,X6	23	11	N/A
Type C	5	1.00 lots/hr	X2,X3,X6	N/A	17	14

4) Throughput at Evaluation < 20 lots/hr
5) Throughput at Removal < 100 units/hr
6) Throughput at Laser Mark < 200 units/hr
7) Throughput at Final Clean < 180 units/hr
8) Throughput at Merge Lot < 300 units/hr
9) Yield is taken into account in variable cost figures.
10) Equipment downtime is included in units/hr (lots/hr) figure

The Personnel Constraints:

1) #Employees < 44
2) #Hours/Employee < 34 hr/week (regular) plus 8 hrs/wk (overtime). This includes 4.5 hr/wk loss due to breaks and lunches and 1.5 hr/wk due to sickness and vacation.
3) #Employee hours/lot at Lot Form = 0.15
4) #Employee hours/reactor hour at Deposition = 0.33

5) #Employee hours/lot at Evaluation = 0.05
6) #Employee hours/unit at Removal = 0.02
7) #Employee hours/unit at Laser Mark = 0.01
8) #Employee hours/unit at Final Clean = 0.006
9) #Employee hours/lot at Final Inspection = 0.15
10) #Employee hours/unit at Merge Lot = 0.003
11) Must have at least one employee in Deposition and Final Clean at all times.
12) #Employee hours for administrative and supervisory tasks = 84

13) #Employee hours for maintenance = 102

Assumptions

Additivity:	The contribution to the objective function for any variable is independent of the values of the other decision variables.
Divisibility:	Each variable is allowed to assume fractional values.
Certainty:	The objective function coefficients, the right-hand-sides, and the technological coefficients are known with certainty.
Discount:	There will be no volume discounts or price negotiations.
Demand:	There is no upper bound for demand for each product type.
Inventory:	Inventory costs are negligible.
Supply:	There is no limitation on raw materials and supply parts. Any delays in obtaining these items is negligible.

Variable Definition

Basis: One week's worth of production. All units are based on one week, unless otherwise noted.

Z = objective function = Profit, normalized

X_{ij} = #Units of product i produced by subprocess j (see below)

i = 1 : 4" Standard process flow
= 2 : 5" Standard process flow
= 3 : 6" Standard process flow
= 4 : 4" Removal process flow
= 5 : 5" Removal process flow
= 6 : 5" NC process flow

j = 1 : Deposition equipment type A
= 2 : Deposition equipment type B
= 3 : Deposition equipment type C

H_k = #Employee hours used by process k

k = 1 : Lot Form and inspection
= 2 : Deposition
= 3 : Evaluation
= 4 : Removal
= 5 : Laser Mark
= 6 : Clean
= 8 : Merge
= 9 : Administrative
=10 : Maintenance

SOLUTION (from LINDO output)

The objective function value is $4272.56. The product mix and allocation of personnel resources per week resulting from the LP are listed below:

# of units produced by Deposition Equipment:

	Type A	Type B	Type C
4" Standard	4056	4760	N/A
5" Standard	0	0	0
6" Standard	N/A	N/A	9412
4" Removal	100	N/A	N/A
5" Removal	100	N/A	N/A
5" No Clean	N/A	0	300

# of employee hours used by:

Lot Form	Deposition	Evaluation	Removal	Laser Marker
165.60	410.34	55.20	4.00	2.00

# of employee hours used by:

Clean	Inspection	Merge	Administration	Maintenance
168.00	165.60	56.19	84.00	102.00

If SEC is forced to produce one unit of any 5" wafer, the profit will decrease by the amount listed in the table below:

	Deposition Equipment:		
	Type A	Type B	Type C
5" Standard	0.056869	0.091406	0.04
5" No Clean	N/A	0.051406	N/A

The model also indicates that 635.0679 hours of personnel are still available for utilization.

With more reactors being considered to produce more 6" wafers, a new product is added to the LP model. As a result, a maximum quantity of 3450 new units per week should be produced by additional reactors for an increase in weekly profit of $2070.00 (i.e., 48.45%). The new process will consume 129.24 employee hours which are already available in the company. It is noted that 6" wafers produced by the new reactor are as good as or better than the 6" wafers produced by reactor type C. Addition of the new reactor still maintains the product mix for other wafers. LINDO model with the new variable added, is shown below;

LINDO Model with new variable X74

```
!
! Optimal productivity and profit through proper allocation of equipment and
! personnel resources.
!
! New variable X74 defined as munber of 6" wafers produced by
! additional new reactor is added to the objective function.
!
! Objective function
!
 MAX    0.19 X11 + 0.19 X12 + 0.27 X21 + 0.27 X22 + 0.27 X23 + 0.42 X33
      + 0.18 X41 + 0.33 X51 + 0.31 X62 + 0.31 X63 + 0.6 X74  - FIXCOST
!
 SUBJECT TO
!
! Product constraints
!
    2)  X11 + X12 >=  100
    3)  X21 + X22 + X23 + X62 + X63 >=  300
    4)  X33 >=  200
    5)  X41 >=  100
    6)  X51 >=  100
!
! Equipment constraints
!
!      Deposition process
!
    7)  0.04762 X11 + 0.09091 X21 + 0.04762 X41 + 0.09091 X51 <=  207
    8)  0.04348 X12 + 0.09091 X22 + 0.09091 X62 <=  207
    9)  0.05882 X23 + 0.07142999 X33 + 0.05882 X63 <=  690
    10)  0.04 X74 <=  138
!
!      Evaluation process
!
    11)  0.04762 X11 + 0.04348 X12 + 0.09091 X21 + 0.09091 X22
   + 0.05882 X23 + 0.07142999 X33 + 0.04762 X41 + 0.09091 X51
   + 0.09091 X62 + 0.05882 X63  + 0.04 X74 <=  3360
!
!      Removal process
!
    12)  X41 + X51 <=  16800
!
!      Clean process
!
```

13) X11 + X12 + X21 + X22 + X23 + X33 + X41 + X51 **+ X74** <= 30240

!
! Merge process
!

14) X11 + X12 + X21 + X22 + X23 + X33 + X41 + X51 + X62 + X63 **+ X74**
<= 50400

!
! **Personnel constraints**
!
! Labor at Lot Form or Final Inspection
!

15) - 0.04762 X11 - 0.04348 X12 - 0.09091 X21 - 0.09091 X22
- 0.05882 X23 - 0.07142999 X33 - 0.04762 X41 - 0.09091 X51
- 0.09091 X62 - 0.05882 X63 **- 0.04 X74** + 6.666667 H1 >= 0

!
! Labor at Deposition
!

16) - 0.04762 X11 - 0.04348 X12 - 0.09091 X21 - 0.09091 X22
- 0.04412 X23 - 0.05357 X33 - 0.04762 X41 - 0.09091 X51 - 0.09091 X62
- 0.04412 X63 **- 0.03 X74** + 2.27 H2 >= 0

!
! At least one employee in Deposition at all time
!

17) H2 >= 168

!
! Labor at Evaluation
!

18) - 0.04762 X11 - 0.04348 X12 - 0.09091 X21 - 0.09091 X22
- 0.05882 X23 - 0.07142999 X33 - 0.04762 X41 - 0.09091 X51
- 0.09091 X62 - 0.05882 X63 **- 0.04 X74** + 20 H3 >= 0

!
! Labor at Removal
!

19) - X41 - X51 + 50 H4 >= 0

!
! Labor at Laser Mark
!

20) - X41 - X51 + 100 H5 >= 0

!
! Labor at Final Clean
!

21) - X11 - X12 - X21 - X22 - X23 - X33 - X41 - X51 **- X74** + 166.67 H6 >= 0

!
! At least one employee in Final Clean at all time
!

22) H6 >= 168

!
! Labor at Merge
!

23) - X11 - X12 - X21 - X22 - X23 - X33 - X41 - X51 - X62 - X63 **- X74**
+ 333.33 H8 >=0

!

```
!     Administration
!
   24)  H9 >=   84
!
!     Equipment Maintenance
!
   25)  H10 >=   127
!
!     Total available labor hours
!
   26)  2 H1 + H2 + H3 + H4 + H5 + H6 + H8 + H9 + H10 <=   1848
!
!     Normalized Fixed Cost
!
   27)  FIXCOST  =   1500

!
 END
```

SENSITIVITY ANALYSIS

The SEC manufacturing problem turns out to be a classic equipment and labor allocation problem. The constraint equations that were defined for LINDO took into account the fact that we had to look at the time taken for each process as well as the labor required for the process. As a result, the LINDO output gave us useful information about shadow prices, allowable ranges, slack or surplus available etc. Since the problem definition already defines the variables as well as the objective function it will not be repeated here. It should be noted however that based on the first LINDO run and the results thereof, some changes were made in the RHS values. This was because it was realized that the available equipment time was not quite as high due to time used in maintenance. Additionally separate labor hours had to be allocated to maintenance to conform with reality. The first LINDO run submitted herewith represents the solution after these iterations.

A major finding of the sensitivity analysis is that the quantities of 5" standard wafers are at zero and the solution only shows 300 of the 5" no clean wafers which is the lower limit for row 3. At the same time a very large RHS range exists for the equation allowing an increase of 11187 without any of the current variables becoming non optimal. As it turns out much larger quantities of 5" standard and 5" no clean wafers are actually produced due to the fact that a number of major customers also need those wafers. Calculations based on the shadow price of row 3 resulted in the following table to indicate the effect of making excess number of above types of wafers;

Table I: Effect of 5" Wafer Quantities on Total # produced and Objective Function

No. of 5" Units Made	Total # Produced	Objective Function
300	18729.58	4272.558
600	18782.539	4261.8
3000	19206.227	4175.75
11487	20704.495	3871.45

It is clear that the objective function can be increased by keeping the number of 5" wafers produced as low as possible. The output of the 6" standard wafers is toggled by the 5" wafers.

The largest objective function coefficient increase required to come into the solution is 0.0914 for 5" standard wafers made in reactor type B. This is not surprising since the product of objective function and reactor capacity is lower for 5" wafers in general compared to 4" wafers. What more, for type B reactors the differential is most pronounced. It is least profitable to use type B reactors for 5" wafers.

Dual prices for rows 7, 8 and 9 representing time of operation constraints for reactors type A, B and C respectively, are quite high at 3.9899, 4.3698 and 5.8798. It is clear that opportunity exists for adding more reactors and/or increase the usage of the current reactors through more effective maintenance to increase the objective function. It is noted that the total labor hours shown in row 25 exhibit a large slack of 635 hours. Additional labor is definitely available to produce more product. Allowable objective coefficient ranges for H1 through H10 are zero. These variables really act as definitions which can be translated into the other product based variables.

Ultimately sensitivity analysis shows that the largest force field for this problem is reactor capacity. A new more efficient 6" single wafer reactor is being considered for increasing capacity. This leads to a new variable X74 defined as the number of 6" wafers produced in reactor 4. Final LINDO runs made after introducing the new variable at an objective function coefficient of 0.6 and reactor lot size of 25, resulted in the production of 3450 wafers and a new objective function value of 6342.56. Analysis of the labor hours shows that only 129.25 additional labor hours are used for the new reactor. A maximum of 4 reactors can be added before we begin to face a maximum labor constraint.

DISCUSSION OF RESULTS

The major results of this work have been reported in previous sections; they are repeated here to facilitate discussion. Formulation and solution of the model led to an increased understanding of the complexity of a seemingly simple manufacturing operation. Unforeseen factors such as yield, equipment downtime, maintenance requirements, employee flexibility, and so on tended to confound the otherwise straightforward model formulation and solution.

The original model formulation had too many variables and did not account for all of the actual process complexity. For example, the original model had intermediate variables to define hours spent and product produced on each type of equipment. In addition, the model contained variables to describe the overall hours spent and product produced from the whole process. On the other hand, the original model did not account for equipment downtime or maintenance personnel requirements. Addition of these constraints brought the model much closer to reality.

The solution of the model led to a striking conclusion. The solution dictates that the company should not produce 5" wafers. This is because 5" wafers have the lowest profit margin. Unfortunately, 5" wafers are the largest segment of the company's business. Large volume purchases tend to drive prices down, while costs remain the same (hence, lower profit margins). The company's Marketing group is actively attempting to shift focus from 5" to 6" wafers (where profit margin is higher). The model concurs with this directive.

As stated in the sensitivity analysis, the opportunity exists for adding more reactors to increase the objective function. If more reactors are added, they should be devoted to producing 6" wafers (if customer demand allows). Company management is currently attempting to purchase more Type C reactors (the only ones capable of producing 6" wafers). The model concurs with this directive.

Solution of the model indicates >600 slack personnel hours, as compared to the fully utilized 44 employee work force (including overtime). This indicates that the company should be able to function with 36 employees without paying overtime. The company actually has 44 employees with an overtime level of about 5%. This discrepancy could be due to several factors. First, the model assumes full flexibility; i.e., every employee can do every task. In reality, most employees only know one or two tasks. This leads to inefficiencies in personnel utilization. Second, the model assumes that the employees are fully effective during their 34.5 hours/week. The model accounts for breaks, lunches, sickness, and vacation. It does not account for meetings, projects, counselings, personal conversations, etc. Further research may reveal the expected magnitude of actual employee effectiveness. Stanfei indicates that using "fairly loose assumptions" for the realities of manufacturing environments in order to use linear programming is reasonable [Stanfei]. Third, the model does not incorporate time spent on some of the "odd jobs" associated with production. Some of these are receiving and storing raw material, tracking work in process (WIP), packaging and shipping finished product, and investigating personnel and equipment problems.

The model predicts that the process can produce 18,000-21,000 wafers/week. This is 30-50% higher than actual production levels. This discrepancy could be caused by several factors. First, it was assumed that each subprocess is independent of the other processes. Unfortunately, this is not completely true. Certain processes can cause problems with other processes. Downtime in one area can cause downtime in other areas (in excess of the downtime accounted for by the model). Second, it was assumed that all equipment is run when it is able to be run. However, equipment can (and does) go idle while operators are absent or on break. Critical areas have been staffed so that coverage is continuous, although the effectiveness of this strategy is not fully understood. Third, it was assumed that all equipment is utilized to its fullest capacity. In reality, actual utilization is variable. Load/unload times vary from operator to operator, setup times vary widely depending on the product being run and the difficulty of the setup, and actual process cycle times vary according to the product being run.

In summary, the model tends to accurately explain general trends in the business situation. It overestimates actual productivity and underestimates actual personnel requirements. Additions and refinements to the model should improve its accuracy in estimating these factors. After the changes are made, the model will be an effective tool for managing the production process. By changing the objective function or constraint equations, the model can be used to minimize overtime, improve training efforts (by identifying the most critical areas for cross-training), predict staffing levels given production changes, predict production levels for equipment changes, and many other useful management functions.

EXTENSIONS

Several areas of modeling and optimizing manufacturing processes for productivity and profit could not be addressed in this one term project. These areas can be divided into three general classes: (1) shop floor control, (2) uncertainty of materials, equipment, and personnel resources, and (3) unconventional approaches.

Shop Floor Control

An in-depth review of schedule and machine queue optimization was thoroughly discussed in the literature search section. Because scheduling is prominent in the literature, additional discussion is warranted. Scheduling is also important because just-in-time inventory control discourages the processing of jobs before or after their due dates. For SEC manufacturing, the industry-wide trend towards make-to-order individual batch lots may require scheduling through critical equipment.

Kops and Natarajan optimize job distributions on machines using linear programming and the principle of time decomposition into constant job-mix stages [Kops]. Their methodology leads to increased utilization of machine tools, higher production rates, shorter makespans of individual jobs, and reduced computational time. However, this method requires significant details of job-mixses.

Rahbar and Rowings show that maintaining a constant production rate and continuity of work for repetitive projects with variable production rates, resource fragmentation, and out-of-sequence progress requires planning time buffers between activities that move resources from one process to another [Rahbar]. Further, approaches using linear optimization which only focus on production rates do not provide a practical solutions. Rahbar and Rowings use linear programming to accomplish line balancing combined with CPM and bar charts to optimize the schedule. This methodology results in a strategic planning tool that indicates the pace of work, allows the planner to exercise judgment, and visualize how everything comes together. Rahbar and Rowings approach to production is well beyond the scope of a single term's project; nonetheless, it is worthy of further consideration.

Resource Uncertainty

A shortcoming of the SEC manufacturing model is the measurement of productive personnel hours given limited cross-training on equipment. The results indicate more available personnel hours than are observed at SEC manufacturing. A better model must be devised to account for employee breaks, material stock-outs, and equipment down time or preventive maintenance. The decision to hire new personnel, purchase new equipment, or invest in cross-training education can be determined only after a model is verified against the actual plant. Several examples appear in the literature.

Yearout et. al. studied the effects of breaks on two typical simulated industrial tasks [Yearout]. The ability to accurately continue a task after a break is a key element in calculating time lost to forgetting. In the study, fifty-eight subjects performed either the traditional peg-board or a spreadsheet graphic for 28 iterations. Upon completion of the assigned task, subjects took a break which ranged from 2 to 83 days. After the break, subjects continued their assigned task. The time subjects took to re-learn the task was developed into an exponential model for the low cognitive task and a multiple linear model for the cognitive task. The author showed how these models assist production managers and industrial engineers in establishing more realistic progress idle time estimates. This same methodology could be applied to SEC manufacturing to better account for employee slack time.

Stern investigates Thatcher's problem [Thatcher] of a continuous processing operation with production and holding costs [Stern]; however, Stern periodically interrupts the arrival of materials. The problem is to minimize the long-term expected value of the total discounted costs. Given that the capacity of the production plant is fixed, and that the demand is constant, and inventory replenishment is stochastic. By minimizing the total costs, a unique long-term "approximate" solution is obtained which is a linear function of the level of inventory at the start of each on-interval and a piecewise linear function of inventory at the start of each off-interval. Stern found the computational results indicate relative cost errors in the order of 2-3 percent.

Akella, Maimon, Bai, and Gershwin demonstrate a goal-based linear program that optimises the work-in-process inventory and tardiness costs for a manufacturing facility with operations, failures, and starvations or blockages [Akella1][Bai]. The scheduling goals keep the production as close to the demand as possible to reduce work-in-process inventory. Processing times are deterministic, but failure and repair times are random. The scheduling is recalculated whenever a machine fails or is starved or blocked. Bai and Gershwin further use the relationship between system capacity and starvation or blockage to optimize the buffer sizes. Although beyond the scope of this class, the above methodologies would positively contribute the the SEC manufacturing paradigm.

Other Approaches

Equipment reliability optimization may also be applicable to the SEC manufacturing problem. For example, a paper by Edwin and Curtius presents an integer-based linear programming method for calculating an optimal annual maintenance schedule for power generation [Edwin]. In their work, the expected annual production cost is minimized and compared with minimizing the system reliability. Their results indicate that reliability methods better balance generator capacity. The same methodology may be applied to the SEC manufacturing problem since equipment downtime is related to capacity.

Another approach offered by Potts and Van Wassenhove is to minimize the weighted number of late jobs in scheduling n independent jobs on a single machine using linear programming [Potts]. They employ a zero-one programming formulation of the problem which yields a lower bound to eliminate jobs from the problem.

In an attempt to reduce numerical calculation time, Lotfi and Chen propose that exact polynomial time algorithms can be developed from linear programs that minimizes the total cost of production and holding [Lotfi]. The algorithms are shown to outperform the general-purpose transportation algorithm for scheduling the size and the timing of production for a multi-item capacitated production facility given a known future demand. The unit production, holding, and resources are linear and time-invariant.

CONCLUSIONS

Problem definition and model formulation are extremely important for solving a problem related to allocation of resources and equipment in a manufacturing facility. Quite often multiple iterations are required to account for unforeseen factors such as yields, downtime, maintenance requirements, raw material inventory and skill level of the labor force. Extensive body of literature exists on the topic with the approaches being divided into three categories. They are resource optimization, schedule optimization and strategic mix optimization.

With maximization of products as a single objective, solution of the final LP and subsequent sensitivity analysis led to the following set of strategies for SEC;

* Minimize production of 5" wafers.
* Obtain additional reactor capacity to increase the output of 6" wafers.
* Perform additional analysis to develop greater understanding of labor utilization.

The first two recommendations were in keeping with the current company strategies. The last recommendation is significant because it leads directly to possible extensions of the project. The discrepancy between the labor requirement in the LP solution and actual labor usage at SEC was significant. Further examination of process interdependence, equipment idle times, and setup times was definitely warranted. In order to incorporate these factors, further refinement of the model is required. Shop floor control, inventory optimization through all stages of process cycle and equipment reliability optimization are some of the methods available to SEC to develop better solutions to this problem and thus achieve better process management. The current model and associated work enabled us to improve our understanding of the problem of equipment and resource allocation. It allowed us to recognize the complexities involved and the multitude of ways in which such problems have been tackled by others in the field.

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