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COMPUTER SIMULATION WITH SENSITIVITY ANALYSIS OF AN ADVANCED COMPOSITE MATERIAL MANUFACTURING OPERATION

by

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Industrial and Systems Engineering

(ABSTRACT)

A computer model is presented which simulates the flow of component orders through an advanced composite material manufacturing operation. The manufacturing operation model simulates actual manufacturing operations by accommodating order-waiting queues and probabilistic rejection rates at each service activity. An inventory model is maintained in parallel with the order flow model to track inventory levels and costs associated with unit consumption, ordering, inventory holding, and shortages.

Tracking of operating costs and sales revenue provides an assessment of system effectiveness in terms of return on investment. Model sensitivity analysis is performed by varying decision and decision-dependent variables in a fractional-factorial designed experiment format. System effectiveness is evaluated for each set of variable conditions in light of probabilistic decision-independent variables.

ACKNOWLEDGEMENTS

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1.0 INTRODUCTION

The increasing competitiveness of national and world markets requires a commitment to continuous improvement in the methods of doing business. In the manufacturing area, these improvements may take the form of reduced unit price, increased product quality, and improved customer service. In any business area, the ability to provide products and services that meet the needs of the customer is the basis for survival, profitability, and growth.

Continuous improvement is a product of continuous, positive change. In most instances, the ability of an organization or individual to change from existing methods is hampered by fear of unknown consequences of the change. Implementing changes that have been tried and proven elsewhere is an effective approach to reducing the risk of unforeseen consequences. However, this strategy ensures that the changing entity if forever relegated to the position of a follower in any endeavor. The risk of bold, revolutionary change can be mitigated by careful analysis and prediction of the effectiveness of alternative courses of action. This analysis and prediction is facilitated by the use of a mathematical model to simulate system performance and sensitivity analyses to assess the impact of changes on selected measures of effectiveness.

The description and results of a project to simulate an advanced composite material manufacturing operation and analyze the model's sensitivity to varying conditions is presented in the following pages. The project is presented as a fanciful case study in which the owner of a small component manufacturing company considers an innovative approach to providing service to his customers. This innovative business approach is based on a statement made several years ago by an aerospace industry executive who is paraphrased as follows:

> "If you can deliver what I want, when I want it, you can name your price."

The explanation for this statement is that the customer's cost of receiving non-conforming or late orders far exceeds the initial order unit cost. Thus, the "high-bid" contractor who consistently meets requirements will ultimately succeed where the low quality, "low-bid", contractor fails.

2.0 REVIEW OF LITERATURE

A limited review of applicable literature was performed to prepare for creation of this project. This entailed a search for examples of statistically-designed experiments (i.e., fractional-factorial arrays) used as the basis for mathematical model sensitivity analyses. Approximately twenty texts in the areas of systems analysis, design of experiments, and statistics, including those in the Northern Virginia Graduate Center (Telestar) Library and the author's library, were reviewed for information which would provide guidance in this investigation. No information on the desired subject was found.

The literature reviewed did provide the background and tools needed to support development of the project described herein. The initial idea for using an experimental design in sensitivity analyses was presented to the author through Citation 6 of the literature cited. Generation of the specific designed experiment used was facilitated by a "hint" offered in Citation 5. The logic for describing and categorizing the system variables was presented in detail in Citation 3. Important tools used in support of this project, such as the computer language used, the spline curve algorithm, and certain statistical methods, were found in Citations 2, 9, and 11, respectively.

3.0 MATERIALS AND METHODS

This section describes the project approach in terms of an industry case study. Included below is a description of the manufacturing operation model, computer simulation, and sensitivity analysis.

3.1 Case Study Overview

The owner and president of Engineered Composite Technology (ECT), Inc., Dr. Ernest A. Bugg, was considering a risky business decision. As a small supplier of specialty and prototype graphite/epoxy components for the aerospace industry, ETC, Inc., had a solid base of customers and had regularly achieved a better than 20-percent annual return on investment (ROI). However, the pending national defense budget cuts and increasing competition from other, larger suppliers had put the future viability of ECT, Inc., in question. The three alternatives Dr. Bugg considered were: (1) continue business as usual and tough-out the hard times ahead; (2) change his basic business approach by offering customers extremely fast order turn-around but at premium prices; or (3) sell out and retire to the old family home, Buggland. In considering option number 2, Dr. Bugg acknowledged that financial backing would likely be available from Megayen, LTD., the Japanese banking conglomerate famous for investing in high-risk, high-payoff ventures.

Dr. Bugg began investigating these business options with a marketing survey directed at his existing and, hopefully, future customers. The results from the survey (customer's views) are summarized as follows:

1) Complete conformance with specifications is absolutely necessary for subcontracted components.

2) A two-month leadtime for the average subcontracted component is considered ideal.

3) Customers would gladly pay a 25-percent premium over the average $80,000 component cost if above items 1 and 2 are met.

Also, the marketing survey indicated that with high-quality and a two-month leadtime, Dr. Bugg could expect approximately 100 orders per year.

Based on these findings, Dr. Bugg approached the people at Megayen, LTD., to discuss financing for a new business entity called Extremely Fast Engineered Composite Technology (EFECT), Inc. The sales pitch to Megayen centered around the results of the marketing survey and Dr. Bugg's knowledge of and reputation in the aerospace supplier community. Furthermore, Dr. Bugg highlighted ETC, Inc's, image as a high-quality manufacturer and his aggressive adoption of the Total Quality Management[1] philosophy.

The Senior Loan Officer at Megayen, LTD., Mr. Zaibatsu, was pensive. Fondling the Rockefeller Center paperweight on his desk, he recalled the many small aerospace firms that, though recently thriving, were now foundering with post-Cold War defense spending cutbacks. His doubts notwithstanding, the loan officer was impressed with Dr. Bugg's presentation and decided to show some encouragement. "Dr. Bugg", said Mr. Zaibatsu, "if you can somehow prove to me that EFECT, Inc., will yield a 20-percent return on investment, then I'll make sure you get the backing you need".

3.2 Operations Simulation Model

Dr. Bugg immediately set to work on a computer model to simulate the operations at EFECT, Inc., as presented in Figure 1. Customers send orders to the Contracts Department, which then release internal production orders to the Planning Department. The Planning Department creates manufacturing and inspection instructions which proceed sequentially through tool fabrication, part fabrication, final inspection/documentation, and the Shipping Department.

In order to accurately reflect real-life operations, the model needed to incorporate features such as order-waiting queues at each department and probabilistic order-arrival rates, service times, and rejection rates. The model must also realistically simulate material inventory dynamics and monitor all critical-cost elements. Dr. Bugg chose to write the computer simulation model in the Quick Basic[2] Programming Language since this was part of the software that came with his newly-purchased Epson Equity I personal computer.

The resulting computer simulation model is presented in Appendix A. Order-arrival rates are modeled as uniformily distributed with an average of 2 per week, 104 per year. As each order arrives, it is randomly assigned a service time in each department according to pre-defined, department-specific service rate probability distributions (uniform or normal). Orders are also assigned a raw material usage between 50 and 100 pounds based on a uniform probability distribution.

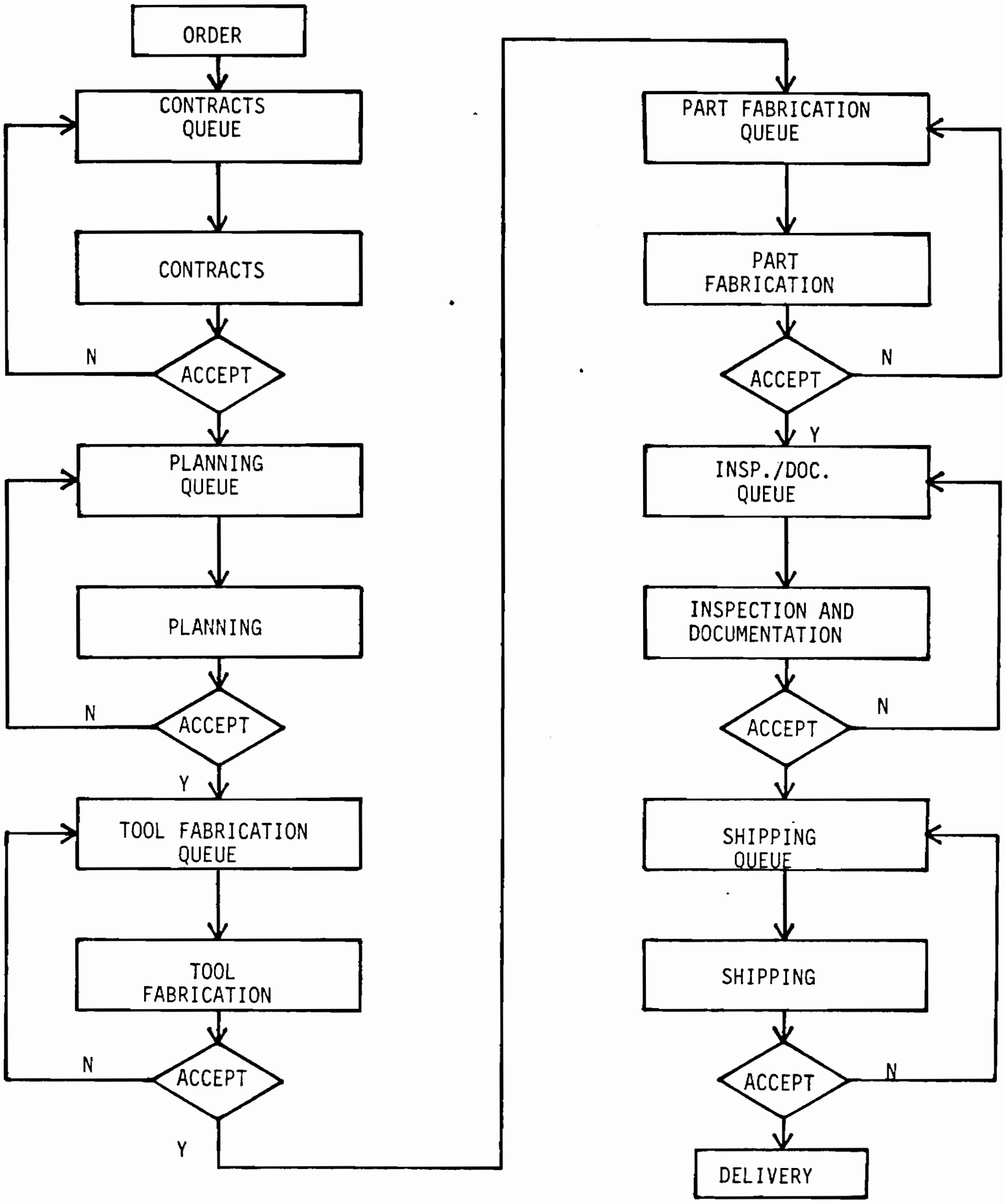


Figure 1. Operations Flow Diagram.

Orders then proceed through the six departments (queue and service center). As orders leave each department, they are subject to rejection and reprocessing at a pre-defined, department-specific rejection rate. The model reassesses the status of each order on a daily basis for up to 1100 days (approximately three years) total simulation run duration.

A raw material inventory status is maintained on a daily basis which monitors order material consumption and replenishment based on a pre-defined material procurement level and procurement quantity. Material delivery leadtime following each procurement varies between 30 and 50 days based on a uniform probability distribution. If the inventory level falls below the material requirement for the next order in the Part Fabrication Department, the material for that order is immediately procured from a competing component supplier at a cost premium.

Order costs are calculated based on department capital costs, labor (with overhead) costs, shipping costs, and material costs. Material costs are calculated as the sum of raw material unit cost ($/lb), inventory holding costs, and procurement cost. The total operating cost elements are further explained in Table I.

The selling price per order is based on a calculation which is unique to and drives the "extremely fast" delivery philosophy of EFECT, Inc. The selling price for each order is calculated by taking a base price of $90,000 plus the expected order material usage multiplied by nominal ($100/lb) material unit cost. The order price is then discounted at a rate of $20 multiplied by the <u>square</u> of the difference between the actual order delivery leadtime and the 60-day advertized

Table I. Description of Operating Cost Components.

Cost Component (Program Variable)	Description
Capital Equipment [CCAP&, CAP&(15)]	Includes the Depreciated Yearly Capital Equipment Cost for All Service Activities
Material Ordering (CORDE&)	Applies a $1000 Order Cost For Each Time Material is Ordered
Unit Materials [CMATL&, MCOST&(500)]	$100/lb for Raw Material From Inventory; $200/lb for Material During Shortage
Inventory Holding (CHOLD&)	$1/lb/Day of Material in Inventory
Shipping Freight (CSHIP&)	Assigns an Average Cost of $200 per Order
Labor Payroll [CSTAFF&, CA%(15)]	Labor Cost Based on an Average Daily Wage Specific to Labor Categories in Each Service Activity; Applied Overhead Accounts For Facility Costs, Benefits, and Indirect Labor and Expenses

leadtime. This pricing strategy is key to the expected success of EFECT, Inc., because it provides the customer with some monitary reparation for large delivery delays and, more importantly, demonstrates EFECT, Inc's, incentive and commitment to on-time delivery.

The basic structure of the computer simulation model describing operations at EFECT, Inc., is applicable to any single-stream, multistep operation with appropriate selection of critical input parameters. The critical parameters specific to the six departments in EFECT, Inc., are presented in Table II. A more detailed evaluation of these critical parameters is presented in the following subsection.

3.3 Model Variables and Effectiveness Function

Sensitivity analysis of the EFECT, Inc., computer model required the evaluation of system effectiveness under various conditions. These various conditions are defined by different combinations of controllable and uncontrollable variables. The effectiveness function (E) can, therefore, be described by the following equation[3]:

$$E = f\ (X, Y_d, Y_i)$$

Where: X = Controllable decision variables

Y_d = Decision-dependent variables

Y_i = Uncontrollable decision-independent variables

The effectiveness function for the EFECT, Inc., model was based on a modified definition of ROI as agreed upon by Dr. Bugg and Mr. Zaibatzu. The ROI is calculated as follows:

Table II. Critical Parameters for the Six EFECT, Inc., Departments.

Department	Nominal Number of Servers (Each)	Daily Labor Cost Per Server ($)	Nominal Yearly Capital Cost Per Server ($)	Nominal Rejection Rate (%)	Nominal Service Time (Days)
Contracts	4	400	2,000	1	3.5
Planning	4	400	2,000	2	7
Tool Fabrication	4	1,000	50,000	4	6
Part Fabrication	15	400	20,000	2	35
Inspection and Documentation	3	400	5,000	2	3
Shipping	3	300	2,000	1	4

$$\mathrm{ROI} = \frac{(S - C_T) \times (1 - t)}{C_T}$$

Where: S = Total sales

C_T = Total costs including depreciation

t = Effective tax rate estimated at 50 percent.

The decision variables included the number of servers in each of the six departments, the raw material inventory order quantity, the raw material inventory order level, and the alternatives available for processing in the Part Fabrication Department. Dr. Bugg decided that the sensitivity analysis must include evaluations of ROI at a median or "best guess" level plus high and low levels for each of the nine decision variables. This would allow the assessment of the rate of ROI variation with respect to decision variable changes. These decision variables and variable levels are described in Table III.

The decision-dependent variables in the computer model are the depreciated capital cost and rejection rate for the Part Fabrication Department. For simplicity, the model provides an inverse linear relationship for capital investment and rejection rate. Thus, capital investments per server of $10,000, $20,000, and $30,000 correspond to rejection rates of 2, 1, and 0.7 percent, respectively. The Part Fabrication Department was the only area where capital investment would have an economically-viable effect on rejection rate with respect to system ROI.

The EFECT, Inc., computer model contains decision-independent variables which are divided into two categories: (1) variable values which are constant through all simulation runs; and (2) variables which

Table III. Controllable System Variable Levels.

Variable Number	Description	Variable Name	Variable Levels Low (-1)	Median (0)	High (+1)
1	Number of Servers in the Contracts Department	NA%(1)	3	4	5
2	Number of Servers in the Planning Department	NA%(3)	3	4	5
3	Number of Servers in the Tool Fabrication Department	NA%(5)	3	4	5
4	Number of Servers in the Part Fabrication Department	NA%(7)	13	15	17
5	Number of Servers in the Inspection/Documentation Department	NA%(9)	2	3	4
6	Number of Servers in the Shipping Department	NA%(11)	2	3	4
7	Raw Material Inventory Order Quantity	D%	900	1,000	1,100
8	Raw Material Inventory Order Level	ORDL%	900	1,000	1,100
9	Processing Options in The Part Fabrication Department	VEST%	1	2	3
9A	Capital Cost per Server in the Part Fabrication Department (Dependent on Variable #9 Decision)	CAP&(7)	10,000	20,000	30,000
9B	Rejection Rate in Part Fabrication Department (Dependent on Variable #9 Decision)	REJ!(8)	0.02	0.01	0.007

are random based on specified probability distributions. The constant decision-independent variables are described in Table IV. These include most of the fixed and recurring cost elements used to calculate values for the effectiveness measure. In addition, there are other constant decision-independent variables which are specific to the model formulation such as the base order cost ($90,000), the order cost multiplier ($\$20/\text{day}^2$), and the selected delivery time threshold (60 days). One other constant, the simulation run duration (three years), is specific to the simulation activity based on a "best guess" as to the run time needed for the model to achieve steady-state conditions.

The randomly distributed decision-independent variables are presented in Table V. For simplicity, all variables are assumed to correspond to a uniform distribution with the exception of service times in the Contracts and Part Fabrication Departments. These were assumed to vary according to a normal distribution.

3.4 Model Sensitivity Analysis

In order to prove to Mr. Zaibatsu that EFECT, Inc., would achieve the 20-percent ROI, a number of simulation runs at each test condition (combination of variable levels) must be performed. This would allow Dr. Bugg to present the probability that EFECT, Inc., would exceed the threshold ROI. Dr. Bugg ran several trial runs of the computer model at selected test conditions to see what would happen.

While performing trial runs of the EFECT, Inc., computer model, Dr. Bugg was struck by the large length of time (approximately 2.5 hours) required to perform one 3-year-long simulation. Dr. Bugg

Table IV. Constant Decision-Independent (Uncontrollable) Variables.

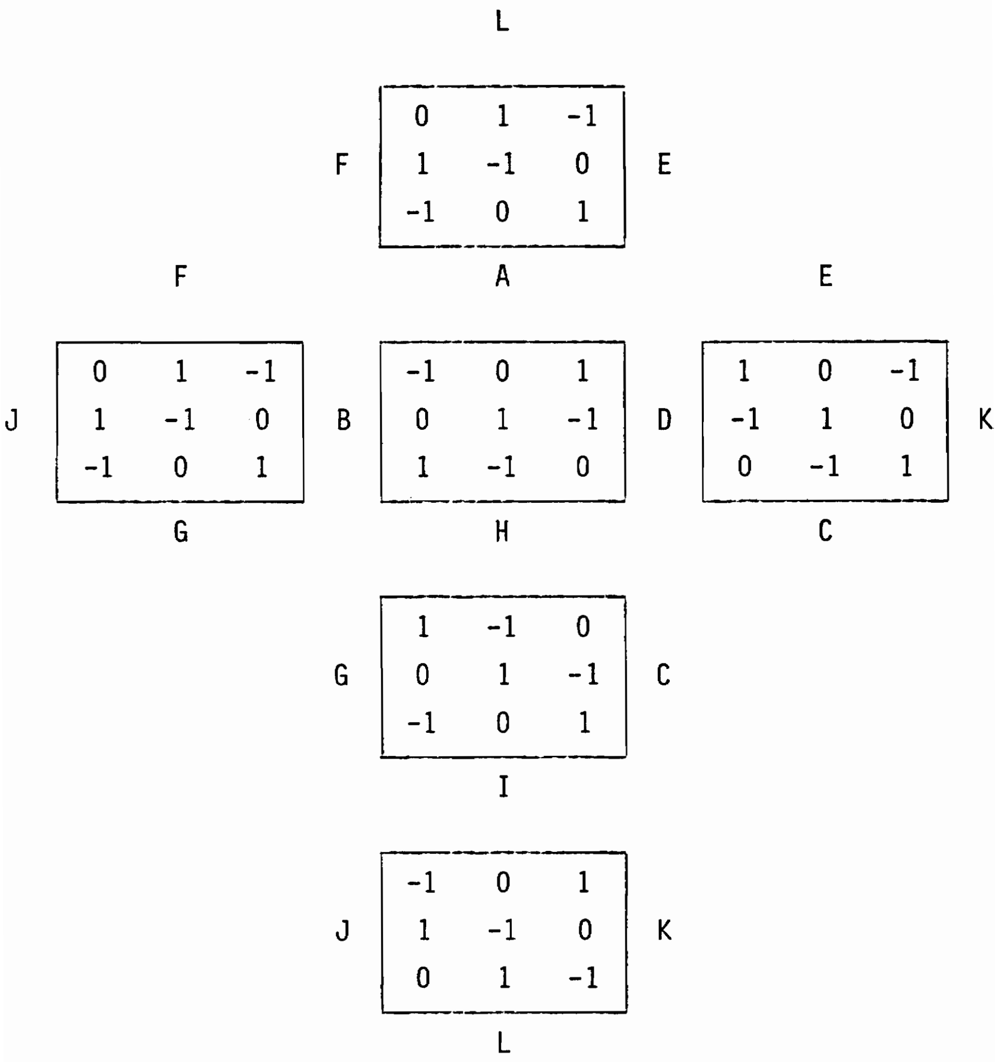
Description	Value
Daily Labor Cost (per Server) for the Contracts Department	$400
Daily Labor Cost (per Server) for the Planning Department	$400
Daily Labor Cost (per Server) for the Tool Fabrication Department	$1,000
Daily Labor Cost (per Server) for the Part Fabrication Department	$400
Daily Labor Cost (per Server) for the Inspection/Documentation Department	$400
Daily Labor Cost (per Server) for the Shipping Department	$300
Capital Cost (per Server) for the Contracts Department	$2,000/Year
Capital Cost (per Server) for the Planning Department	$2,000/Year
Capital Cost (per Server) for the Tool Fabrication Department	$50,000/Year
Capital Cost (per Server) for the Inspection/Documentation Department	$5,000/Year
Capital Cost (per Server) for the Shipping Department	$2,000/Year
Raw Material Inventory Holding Cost per Day	$1/lb
Average Shipping Cost per Order	$1/Day
Raw Material Ordering Cost	
Material Inventory Holding Cost per Pound	$1/Day
Material Unit Cost per Pound (Shortage Cost per Pound)	$100 ($200)
Average Order Shipping Cost	$200
Base Price per Order (Base Price Multiplier)	$90,000 $\$20/\text{Day}^2$

Table V. Probabilistic Decision-Independent (Uncontrollable) Variables.

Description	Distribution Type	Mean	Standard Deviation
Order Arrival Rate	Uniform	2/Week	1.15
Service Time in Contracts Department	Normal	3.5 Days	0.5
Service Time in Planning Department	Uniform	7 Days	1.15
Service Time in Tool Fabrication Department	Uniform	6 Days	1.15
Service Time in Part Fabrication Department	Normal	35 Days	2
Service Time in Inspection/Documentation Department	Uniform	3 Days	0.58
Service Time in Shipping Department	Uniform	4 Days	0.58
Rejection Rate in Contracts Department	Uniform	1%	0.58
Rejection Rate in Planning Department	Uniform	2%	1.15
Rejection Rate in Tool Fabrication Department	Uniform	4%	2.3
Rejection Rate in Inspection/Documentation Department	Uniform	2%	1.15
Rejection Rate in Shipping Department	Uniform	1%	0.58
Raw Material Usage Per Order	Uniform	75 lbs	14.4
Raw Material Delivery Time	Uniform	40 Days	5.8

discovered that this cycle time was typical for an 286-chip computer running the Quick Basic Interpreter rather than a "compiled" GW Basic[4] Program. Even when Dr. Bugg ran the simulation trial on a 386-chip computer, the run time was 20 minutes. Although considerably faster, the 20-minute cycle time presented a problem if he was to evaluate all nine decision-dependent variables at three levels each. This would require a run time of three raised to the ninth power times 20 minutes, or 393,660 minutes (6,561 hours or 273 days). This run time was based on evaluating a full-factorial array of decision variable level combinations with no replications at any condition. Since this total run time was clearly untenable, Dr. Bugg decided to develop a fractional-factorial array of decision variable level combinations to reduce the total number of simulation runs required.

Dr. Bugg reviewed some of the literature[5] on statistically-designed experiments to learn how to create a three-level fractional-factorial array. Unfortunately, the only reference which addressed the creation of these types of experimental designs did not explicitly describe the procedure for establishing the array. Rather, the reference indicated that three-level, fractional-factorial arrays of the type required could be "generated" using a Latin cube. Based on his understanding of the Latin square, Dr. Bugg created the Latin cube shown as a planar projection in Figure 2. In the Latin cube, each of the six sides of a cube is a Latin square with three rows and three columns containing the three variable levels (-1, 0, 1). The six Latin squares are devised such that the variable level values at any two adjoining edges are equal. In



						L						
					0	1	-1					
				F	1	-1	0	E				
					-1	0	1					
		F				A				E		
	0	1	-1		-1	0	1		1	0	-1	
J	1	-1	0	B	0	1	-1	D	-1	1	0	K
	-1	0	1		1	-1	0		0	-1	1	
		G				H				C		
					1	-1	0					
				G	0	1	-1	C				
					-1	0	1					
						I						
					-1	0	1					
				J	1	-1	0	K				
					0	1	-1					
						L						

Figure 2. Latin Cube Used to Generate Experimental Array With Three Levels per Variable.

Figure 2, these edges are designated by the letters A through L. To generate the three-level fractional-factorial array for nine variables, one begins with a full-factorial array for three variables ($3^3 = 9$ combinations) as shown by columns A, B, and C in Table VI. The fourth column, D, is generated from the Latin cube by finding the intersecting value on the Latin square containing A and B which corresponds to each variable level value in columns A and B. For example, for condition 10 in Table VI, the level values for A and B are 0 and 1, respectively. In Figure 2, these correspond to a level value for D of -1. Thus, experimental array columns are generated from previous columns using the Latin cube. A quick mathematical check verified that all variable levels in Table VI were equally represented in a balanced, orthogonal array.

The resulting overall sensitivity analysis format is represented by Figure 3.[6] Each test series, or test conditions, defines an ordered combination of decision variable levels according to a fractional-factorial "inner" array. The decision variable X_d is included to represent the implicit decision-dependent variables. An "outer" array of noise sources contains the randomly-varying decision-independent variables (R). The test series, 1 through j, and noise conditions, 1 through i, define the array of resulting system effectiveness function values (E_{ij}). Thus, the sensitivity analysis consists of a simulation run at j conditions with i trials per condition. This arrangement of inner and outer arrays is similar to the Parameter Design methodology presented by Taguchi[7] except that Taguchi defines specific high and low values for the decision-independent variables in the outer array.

Table VI. Experimental Array Generation.

VARIABLE	1	2	3	4	5	6	7	8	9
DESIGNATION	A	B	C	D	E	F	G	H	I
GENERATOR	–	–	–	AB	DC	AE	BF	AD	GH
CONDITION 1	1	1	1	0	1	1	0	0	-1
CONDITION 2	1	1	0	0	0	0	-1	0	1
CONDITION 3	1	1	-1	0	-1	-1	1	0	0
CONDITION 4	1	0	1	-1	0	0	1	-1	-1
CONDITION 5	1	0	0	-1	-1	-1	0	-1	1
CONDITION 6	1	0	-1	-1	1	1	-1	-1	0
CONDITION 7	1	-1	1	1	-1	-1	-1	1	-1
CONDITION 8	1	-1	0	1	1	1	1	1	1
CONDITION 9	1	-1	-1	1	0	0	0	1	0
CONDITION 10	0	1	1	-1	0	-1	1	1	1
CONDITION 11	0	1	0	-1	-1	1	0	1	0
CONDITION 12	0	1	-1	-1	1	0	-1	1	-1
CONDITION 13	0	0	1	1	-1	1	-1	0	1
CONDITION 14	0	0	0	1	1	0	1	0	0
CONDITION 15	0	0	-1	1	0	-1	0	0	-1
CONDITION 16	0	-1	1	0	1	0	0	-1	1
CONDITION 17	0	-1	0	0	0	-1	-1	-1	0
CONDITION 18	0	-1	-1	0	-1	1	1	-1	-1
CONDITION 19	-1	1	1	1	-1	0	-1	-1	0
CONDITION 20	-1	1	0	1	1	-1	1	-1	-1
CONDITION 21	-1	1	-1	1	0	1	0	-1	1
CONDITION 22	-1	0	1	0	1	-1	0	1	0
CONDITION 23	-1	0	0	0	0	1	-1	1	-1
CONDITION 24	-1	0	-1	0	-1	0	1	1	1
CONDITION 25	-1	-1	1	-1	0	1	1	0	0
CONDITION 26	-1	-1	0	-1	-1	0	0	0	-1
CONDITION 27	-1	-1	-1	-1	1	-1	-1	0	1

OUTER ARRAY

Decision-Independent Variables	1	2	3	·	·	·	i
	R_{31}	R_{32}	R_{33}	·	·	·	R_{3i}
	R_{21}	R_{22}	R_{23}	·	·	·	R_{2i}
	R_{11}	R_{12}	R_{13}	·	·	·	R_{1i}

INNER ARRAY

Test Series	Decision Variables									
	X_1	X_2	X_d							
1	-1	0	+1	E_{11}	E_{21}	E_{31}	·	·	·	E_{i1}
2	+1	-1	0	E_{12}	E_{22}	·	·	·	·	·
3	0	+1	-1	E_{13}	·	·	·	·	·	·
·	-	-	-	·	·	·	·	·	·	·
·	-	-	-	·	·	·	·	·	·	·
·	-	-	-	·	·	·	·	·	·	·
·	-	-	-	·	·	·	·	·	·	·
j	+1	0	-1	E_{1j}	·	·	·	·	·	E_{ij}

Figure 3. Sensitivity Analysis Using a Factorial Decision Variable Array and Randomly Generated Noise Source Array.

Dr. Bugg's use of this sensitivity analysis format required 270 simulation runs (27 conditions x 10 runs each) at 20 minutes apiece for a total run time of 5,400 minutes or 90 hours. Dr. Bugg was able to perform the sensitivity analysis and subsequent evaluation of results in a reasonable length of time while using existing computation facilities.

4.0 RESULTS

The output from the EFECT, Inc., computer model sensitivity analysis is presented in Table VII. The decision variables 1 through 9 correspond to the controllable system variables described previously in Table III. For each test condition, ten simulation runs yielded ten values for the system effectiveness ROI and a calculated ROI Mean ($\bar{X}$) and standard deviation (S). Based on an assumption that the ROI generated for each test condition followed a normal distribution, the mean and standard deviation were used to calculate a probability (P) that the ROI for that test condition would exceed 20 percent. The computer program used to perform these calculations is presented in Appendix B.

The average effect of each decision-variable level on the probability (P) of exceeding 20-percent ROI was computed using the computer program presented in Appendix B. This computer program calculated the average P-value for each variable level as shown in Table VIII. These results, presented graphically in Figure 4, indicated that the highest P-value would be achieved with decision-variable settings as follows:

Variable	1	2	3	4	5	6	7	8	9
Setting	M	M	L	L	L	L	M	M	L
Value	4	4	3	13	2	2	1000	1000	1

(L = Low, M = Median)

Table VII. Results of the EFECT, Inc., Simulation and Sensitivity Analysis

	DECISION VARIABLES									SIMULATION RUN										AVER.	STD. DEV.	PROB.
TEST	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9	10	x	s	p
1	5	5	5	15	4	4	1000	1000	1	15.8	13.4	13.9	14.5	10.1	15.1	13.3	9.5	13.2	15.5	13.4	2.1	.0009
2	5	5	4	15	3	3	900	1000	3	20.3	16.5	12.8	20.4	19.3	17.0	14.3	16.7	14.9	17.1	16.9	2.5	.1110
3	5	5	3	15	2	2	1100	1000	2	29.9	22.6	20.8	25.8	24.4	25.9	30.2	27.0	27.6	18.9	25.3	3.7	.9245
4	5	4	5	13	3	3	1100	900	1	18.9	20.6	17.0	20.8	20.3	24.8	17.9	18.3	18.6	17.6	19.5	2.3	.4044
5	5	4	4	13	2	2	1000	900	3	26.0	27.6	21.7	21.7	18.8	25.6	23.4	24.1	24.3	24.1	23.7	2.5	.9295
6	5	4	3	13	4	4	900	900	2	26.4	22.6	19.9	21.2	18.5	25.8	19.2	22.0	21.8	22.7	22.0	2.6	.7819
7	5	3	5	17	2	2	900	1100	1	8.9	18.2	15.1	16.2	19.8	19.1	13.0	14.1	11.6	14.6	15.0	3.4	.0731
8	5	3	4	17	4	4	1100	1100	3	15.1	15.6	12.9	11.4	16.7	11.4	19.4	12.4	11.6	17.4	14.4	2.9	.0246
9	5	3	3	17	3	3	1000	1100	2	15.6	17.8	24.5	19.0	20.7	21.3	21.7	18.2	17.0	15.4	19.1	2.9	.3785
10	4	5	5	13	3	2	1100	1100	3	20.4	9.8	18.8	11.0	15.2	18.3	17.3	23.1	14.7	22.4	17.1	4.5	.2557
11	4	5	4	13	2	4	1000	1100	2	18.9	27.1	21.6	24.5	25.8	23.1	22.3	20.0	23.1	18.8	22.5	2.8	.8127
12	4	5	3	13	4	3	900	1100	1	28.4	25.9	22.6	24.9	20.8	26.0	17.4	21.4	26.6	21.4	23.1	2.9	.8563
13	4	4	5	17	2	4	900	1000	3	9.5	12.9	17.1	18.3	15.7	13.0	11.0	15.2	12.8	13.9	13.9	2.7	.0125
14	4	4	4	17	4	3	1100	1000	2	13.0	16.2	21.6	10.1	18.7	13.8	15.0	18.6	19.5	21.7	16.8	3.8	.2020
15	4	4	3	17	3	2	1000	1000	1	27.0	21.6	22.2	22.3	20.8	18.2	21.0	22.2	19.3	21.3	21.6	2.3	.7485
16	4	3	5	15	4	3	1000	900	3	13.0	20.0	15.8	17.9	15.0	14.5	13.4	10.3	18.2	16.7	15.5	2.9	.0562
17	4	3	4	15	3	2	900	900	2	18.7	20.1	23.5	17.8	19.7	23.6	19.6	22.0	22.2	23.2	21.0	2.1	.6814
18	4	3	3	15	2	4	1100	900	1	19.8	26.6	26.7	25.9	26.6	22.6	24.7	29.1	25.4	29.9	25.7	2.9	.9748
19	3	5	5	17	2	3	900	900	2	13.5	15.8	12.6	12.8	18.5	14.9	12.8	16.8	13.5	16.5	14.8	2.0	.0051
20	3	5	4	17	4	2	1100	900	1	18.7	19.5	16.1	19.5	13.5	17.5	17.5	17.3	15.8	14.3	17.0	2.0	.0666
21	3	5	3	17	3	4	1000	900	3	20.6	11.8	16.2	19.3	19.9	19.8	24.6	13.4	19.1	17.6	18.2	3.7	.3128
22	3	4	5	15	4	2	1000	1100	2	16.4	18.4	14.0	18.2	18.6	12.8	19.4	16.6	17.2	23.2	17.5	2.9	.1900
23	3	4	4	15	3	4	900	1100	1	25.0	20.7	20.8	15.7	18.3	21.4	21.2	17.8	16.4	20.3	19.8	2.7	.4611
24	3	4	3	15	2	3	1100	1100	3	24.6	34.3	31.3	29.8	20.8	26.9	30.5	27.4	24.6	26.8	27.7	3.9	.9751
25	3	3	5	13	3	4	1100	1000	2	22.4	15.8	12.7	24.9	19.0	21.2	21.0	26.8	19.8	19.6	20.3	4.1	.5284
26	3	3	4	13	2	3	1000	1000	1	22.3	23.6	28.2	30.1	32.4	25.9	27.9	22.6	28.9	28.3	27.0	3.4	.9813
27	3	3	3	13	4	2	900	1000	3	25.2	28.5	33.2	30.7	28.4	33.2	31.6	30.9	29.3	34.0	30.5	2.7	.9999

Table VIII. The Average Effect of Each Variable Level.

Variable	Low (-1)	Median (0)	High (1)
1	50.23	51.11	40.32
2	52.20	52.28	37.17
3	77.25	47.45	16.96
4	72.78	48.61	20.26
5	63.21	43.13	35.32
6	54.10	44.11	43.44
7	44.25	49.01	48.40
8	46.81	50.10	44.75
9	50.75	50.05	40.86

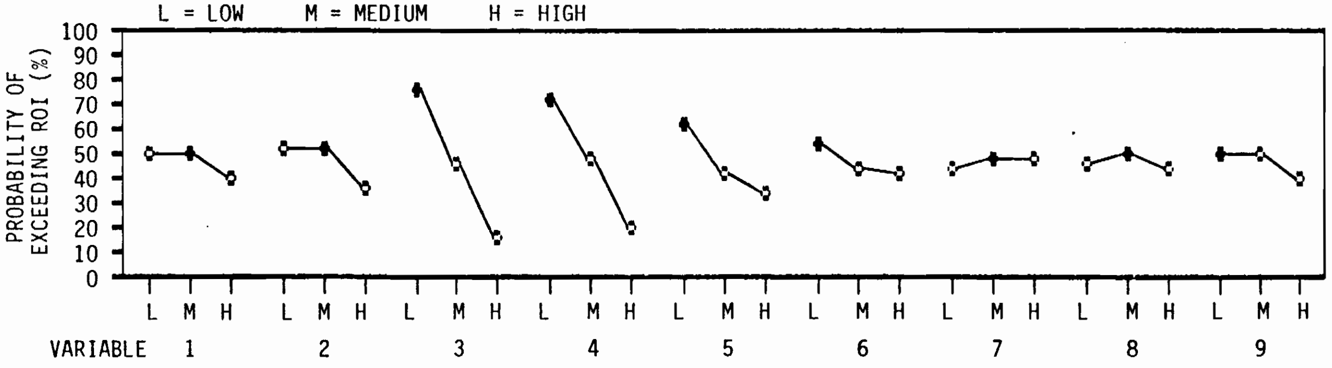


Figure 4. The Average Effect of Each Variable Level on the Probability of Exceeding the Baseline Return on Investment (20-Percent ROI).

The EFECT, Inc., computer model presented in Appendix A was modified to perform ten simulation runs with the decision variables set at the levels specified above. The result of this verification simulation series was a mean ROI of 32.7 percent, ROI standard deviation of 2.4, and a P-value in excess of 0.9999. This result was significantly better than the best initial test condition result (#27) of ROI mean = 30.5 percent and ROI standard deviation of 2.7. Therefore, this "optimum" set of decision-variable levels was used for further computer model verification[8] (note that this "optimum" result is valid only within the range identified for the discrete variable levels).

Verification of the EFECT, Inc., computer model and the results obtained thus far was performed by comparing key model output parameters with subjectively-defined acceptability criteria. The modified Appendix A computer model, described above, was further modified to provide total order flow times as output. Order flow times (delivery date minus ordering date) plotted in sequence of shipment are presented in Figure 5. The mean order flow time of approximately 63 days is indicated. In addition, financial data was generated in two plots as follows: (1) Figure 6 - average order unit cost and total operations cost per time; and (2) Figure 7 - total operations cost and total invoices versus time. Figures 5, 6, and 7 represent key EFECT, Inc., system parameters evaluated over a three-year period in order to assess model fidelity with anticipated real-life operating conditions. The cubic spline curve fitting computer program[9] created to embellish Figures 6 and 7 is presented in Appendix C.

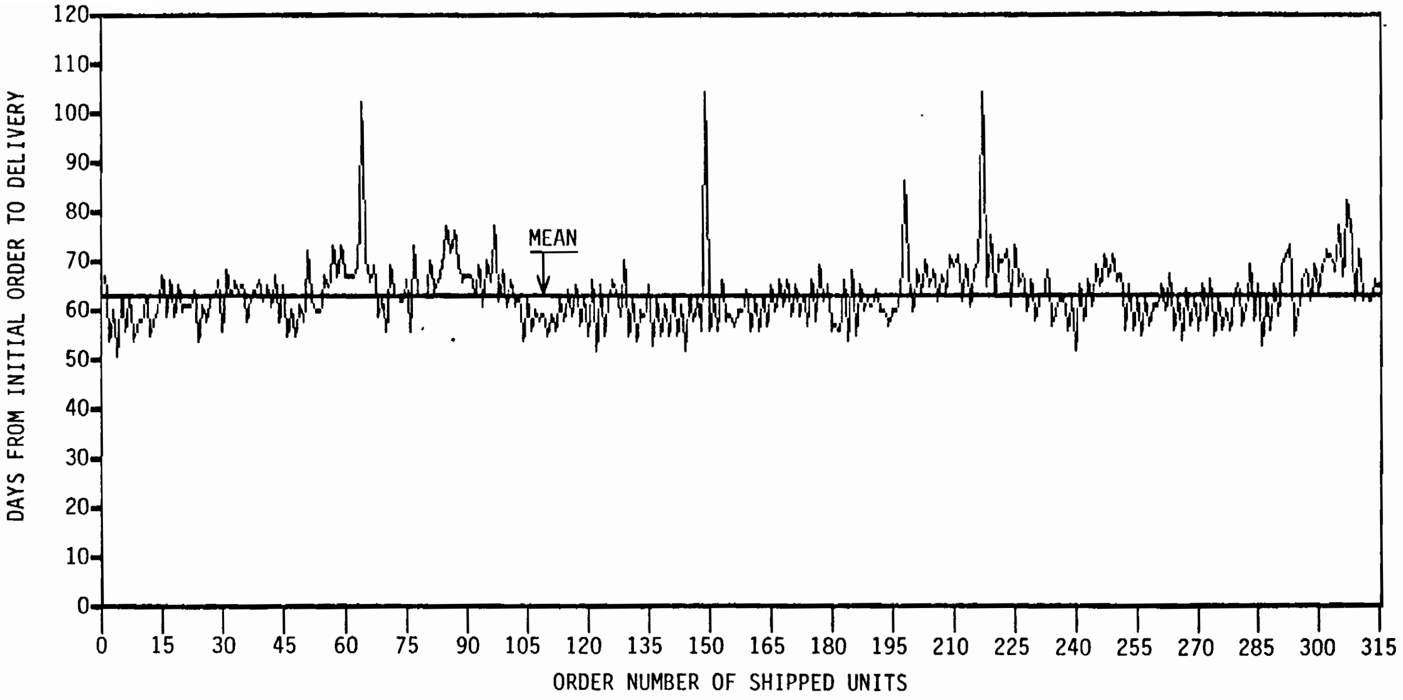


Figure 5. Total Order Flow Times Versus Shipping Number.

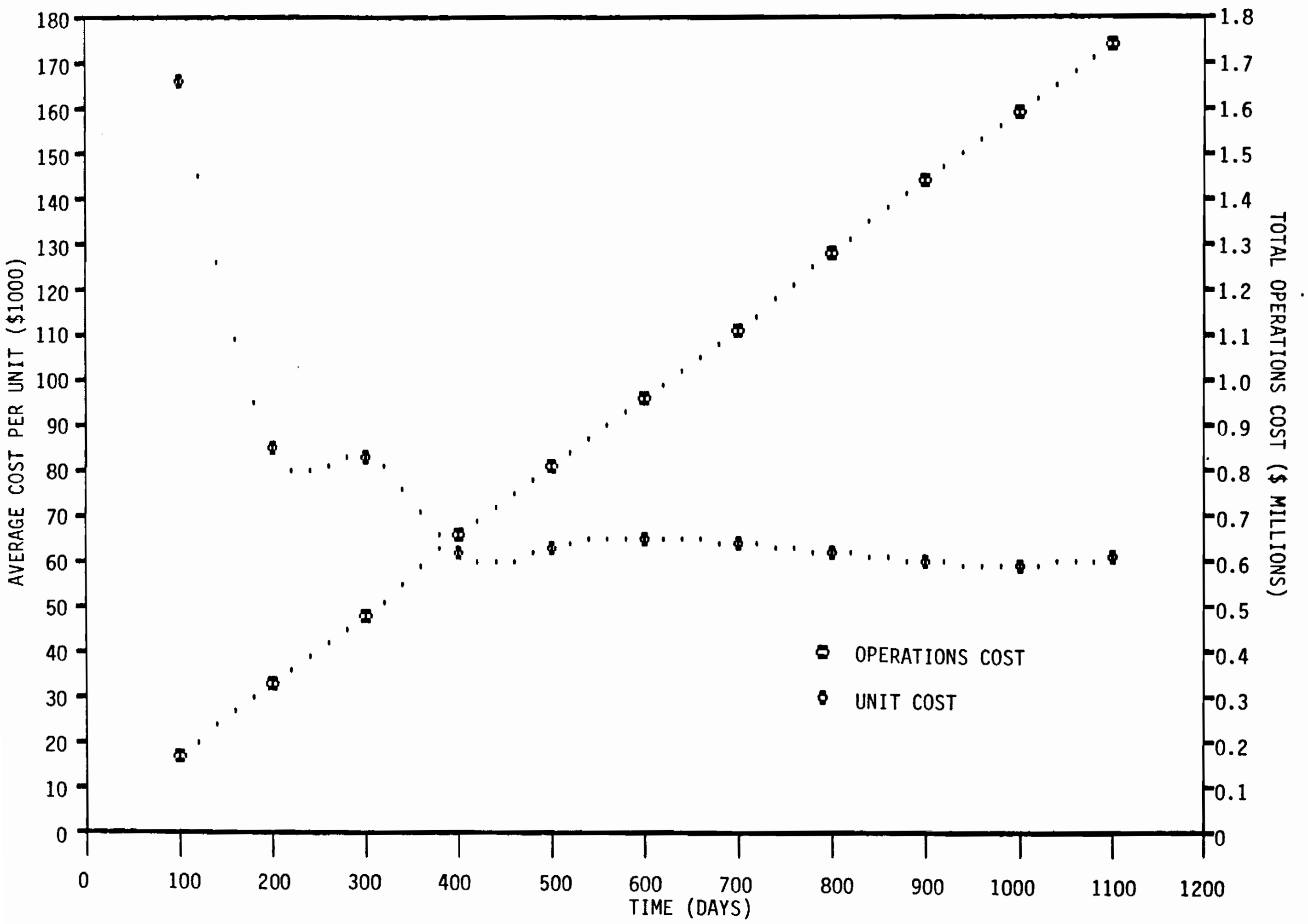


Figure 6. Total Operations Cost and Unit Cost Versus Time.

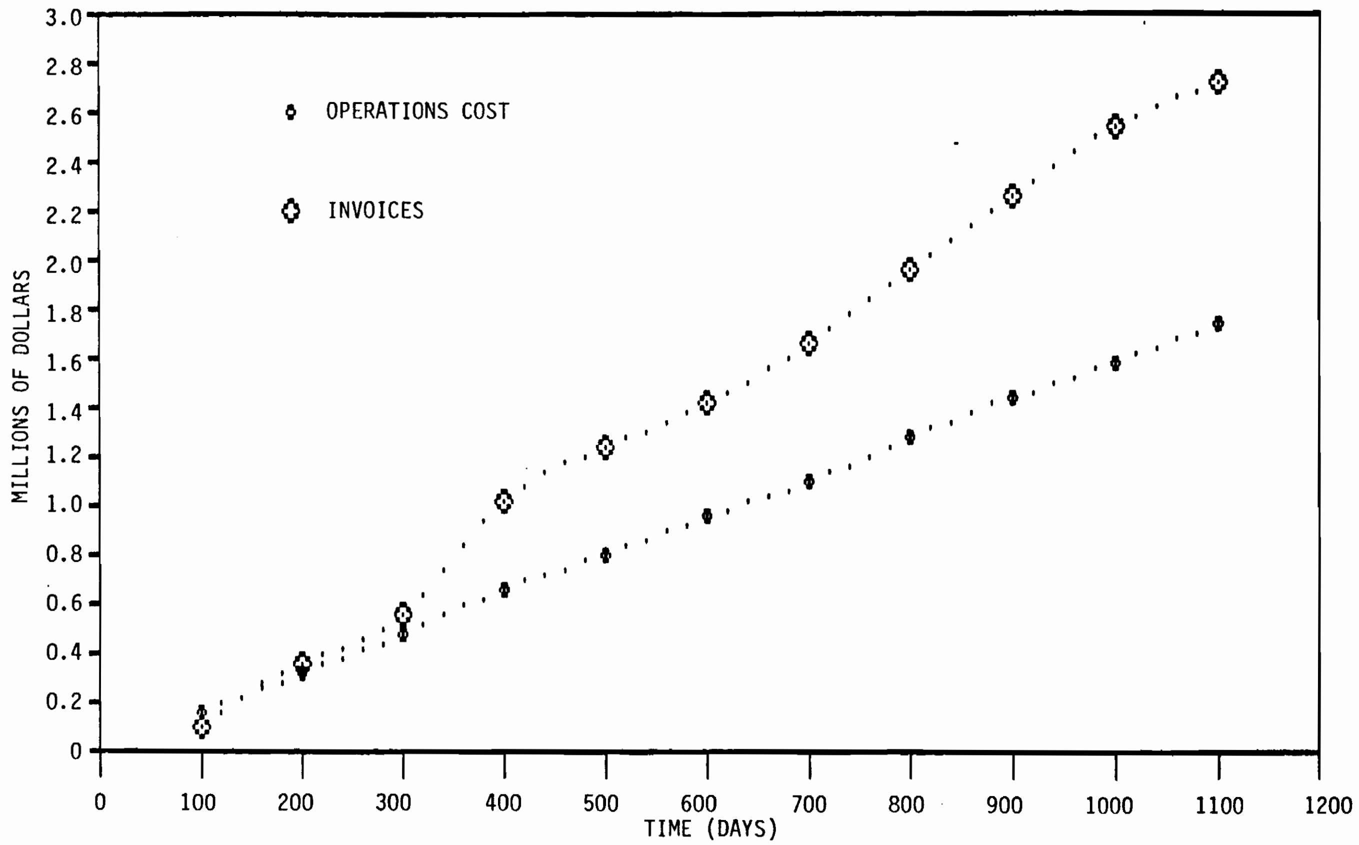


Figure 7. Total Operations Cost and Total Invoices Versus Time.

A modified Appendix A computer simulation using "optimum" design variable level settings was also run to assess the dynamics of the EFECT, Inc., raw material inventory system. The results of this assessment are presented in Figure 8 with the plot of raw material inventory versus simulation run time. This plot was then compared with a published[10] inventory cycle plot on a qualitative basis.

While performing this model verification, Dr. Bugg reviewed the model results with an emphasis on the ROI $\overline{X}$-, S-, and P-values. Calculations thus far had been performed without consideration for statistical confidence levels and, therefore, represented point estimates of system effectiveness. In light of this, Dr. Bugg modified the computer program in Appendix B to use a mean ROI based on ten observations (ten simulation runs) adjusted to the lower confidence limit at a 99-percent confidence level[11] as follows:

$$\overline{X}_{LCL} = \overline{X} - t_{.99} \frac{S}{\sqrt{10}}$$

Where: $\overline{X}$ = Mean ROI

S = ROI standard deviation

$t_{.99}$ = Student's distribution coefficient with 10-1 = 9 degrees-of-freedom at a 99-percent confidence level

The computer program in Appendix B was used to determine the average P-value of each variable level with the resulting "optimum" decision variable level set:

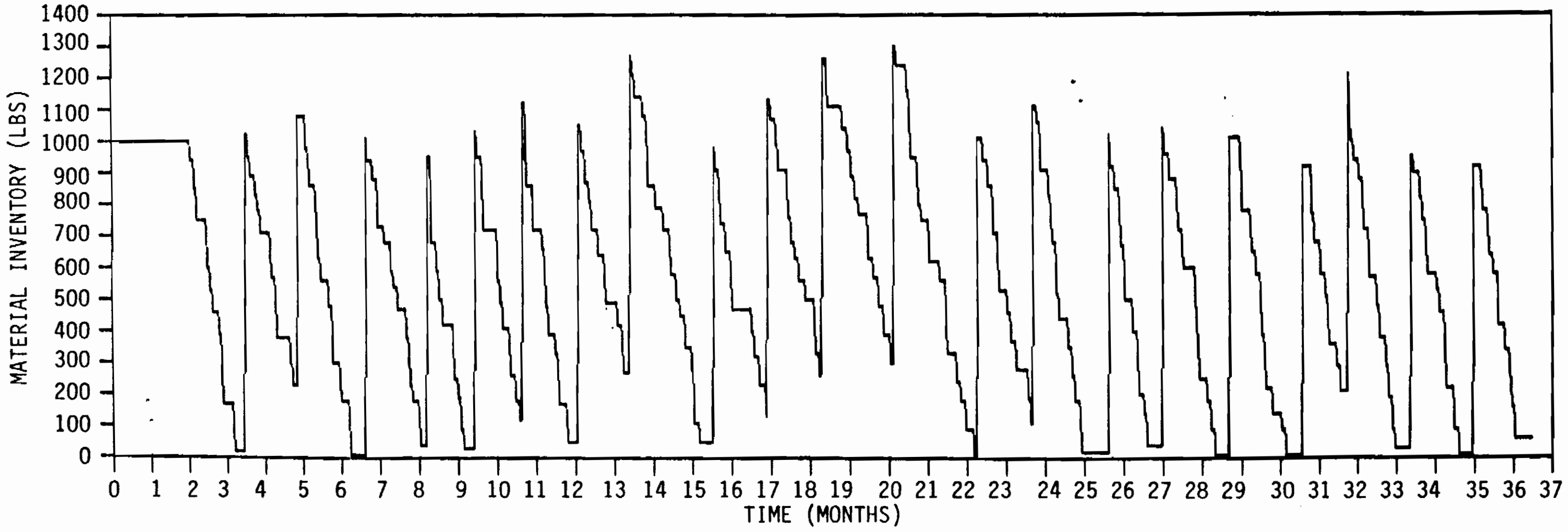


Figure 8. Inventory Profile Versus Time for Graphite/Epoxy Raw Material.

Variable	1	2	3	4	5	6	7	8	9
Setting	L	L	L	L	H	L	H	L	H
Value	3	3	3	13	4	2	1100	900	3

(L = Low, M = Median, H = High)

A ten-run simulation of Appendix A with the above design variable settings yielded a mean ROI of 34.6 percent, ROI standard deviation of 2.1, and a P-value well in excess of 0.9999. Though somewhat puzzled by these results, Dr. Bugg made an appointment to present his findings to Mr. Zaibatsu at Megayen, LTD.

5.0 DISCUSSION

The results of the computer model simulation and sensitivity analysis were largely successful in demonstrating the potential profitability of EFECT, Inc. The simulation model appeared to accurately depict the flow of orders through the factory and generated reasonable output in the form of flow time, cost, and inventory dynamic parameters. The sensitivity analysis approach using the fractional-factorial array format was successful in assessing system effectiveness over a range of operating conditions within the given modeling constraints. However, some questions remained as to the statistical validity of the results and, in particular, the identification of optimum operating conditions.

Mr. Kaibatsu's initial question concerned the selection of probability distributions to model order arrival rates, service times, rejection rates, and raw material consumption. Past studies have shown that these variables often follow Poisson or exponential distributions, while the computer model used uniform and normal distributions exclusively. Dr. Bugg responded by saying that the short-term objective was to model the random nature of those decision-independent variables. For this effort, the easiest and quickest way to model these was via uniform distributions using the random number generator within the existing software. In isolated instances, such as the Contracts and Part Fabrication Department service times, the normal distribution more accurately represented operations within Dr. Bugg's experience.

Mr. Kaibatsu then asked about the graph (Figure 5) showing average order flow times. Although the average flow time was 63 days and very near the 60-day goal, some isolated peaks indicated that some orders were extremely late in delivery. Dr. Bugg pointed out that these were due to the sort of random rejections and reworks associated with normal operations. Furthermore, the second-order pricing function offered the delayed customer significant compensation for those late deliveries. Mr. Kaibatsu and Dr. Bugg agreed, however, that additional work was necessary to provide more uniform service and total flow times. This corrective action may take the form of improved training or tooling to reduce catastrophic rejection rates or perhaps some sort of redundancy in specific operations for certain failure-prone configurations.

Another of Dr. Kaibatsu's questions addressed the simulation run duration and the achievement of model steady-state operations. Dr. Bugg revisited the cost profiles in Figures 6 and 7. In Figure 6, the unit order cost began at a very high value ($170K), but finally settled to a relatively constant vaue of $60K by day 400. Meanwhile, the total operations costs continued to climb over the same period of time in a nearly-linear fashion. The total operating cost and total invoices curves presented in Figure 7 did not confirm or refute the claim that a steady-state condition was reached in the model. Dr. Bugg agreed with Mr. Kaibatsu that a longer simulation run of approximately five years would probably resolve the issue.

Perhaps the most impressive demonstration of the model veracity was presented by the raw material inventory model in Figure 8. It reflected the gradual depletion of raw material inventory followed by sudden jumps at resupply. The lack of a sharp point on the lower inventory curves indicated that material had been procured from emergency sources when supply ran low. Extrapolation of the lower portions of the cycle curve below the zero-inventory level would certainly dramatize the incidence of material shortage. Dr. Bugg noted that the use of a uniform distribution to describe raw material order time was completely arbitrary.

Two additional major problems with the simulation model were identified by Mr. Zaibatsu. First, the lack of a discounted cash flow basis for the expenditures and invoices detracted from the overall credibility and accuracy of the cost accounting. Second, the capital investment per server in each department was not multiplied by the number of years in the simulation run. The three-year run, therefore, created a capital investment depreciation of one-third of the anticipated value. However, this error existed in all computations and did not bias the analysis results. Dr. Bugg defended his use of non-discounted cash flows as the easiest, quickest approach to simulation model development; however, discounted cash flow rates could be included in future simulations. Dr. Bugg was surprised by the programming error in the capital cost accounting area. This error also could be addressed in a future simulation.

Dr. Zaibatsu was generally pleased with the approach to sensitivity analysis used by Dr. Bugg. One of its most attractive features was the logical layout of the inner decision-variable array and outer decision-independent variable array. However, Mr. Zaibatsu suspected that too many variables were being considered in a very small decision-variable array. Dr. Bugg confirmed that there was a potential problem with the effect of each variable being obscured, or confounded, with other variable effects. This seemed to be the problem indicated when the lower confidence limits were applied to the mean ROI values. The optimum test condition identified using the point estimate mean ROI's should have yielded a higher ROI, lower ROI standard deviation, and higher P-value than the optimum test condition identified at the 99-percent confidence level. Instead, the reverse was true, leading to the conclusion that variable effect confounding had slanted the results.

Dr. Kaibatsu was pleased with the results of the modeling and sensitivity analysis technique. This simulation provided a reasonable assessment of EFECT, Inc's, profitability based on the assumptions made by Dr. Bugg. Moreover, it identified the direction to pursue to achieve optimal return on investment and identified potential pitfalls in the operation. Dr. Kaibatsu was convinced that EFECT, Inc., would be able to deliver the required 20-percent ROI.

6.0 CONCLUSIONS

From Dr. Bugg's point of view, the model development and sensitivity analysis were an unqualified success. The model accurately represented the manufacturing operations at EFECT, Inc., and the sensitivity analysis provided a low cost and timely evaluation of a high risk business decision. Dr. Bugg and Mr. Zaibatsu lived happily ever after.

The computer model was indeed a success in depicting the complex and dynamic nature of the manufacturing operation. The use of randomly-varying quantities for order arrival rate, raw material usage, service times, rejection rates, and raw material delivery times made the model seem at times like an unpredictable living entity. In addition to modeling the functional aspects of the factory, such as reject/rework cycles and raw material inventory, the computer simulation accurately represented all critical cost elements including inventory shortage costs and a delivery schedule-dependent order pricing strategy. The major flaw in the model was the assumption of constant-time money value used for simplicity in cost accounting.

Use of a fractional-factorial array for performing the sensitivity analysis provided a logical format for variable organization and a methodology for optimization. As in the case study presentation, the constraints of time and computational resources made this approach to sensitivity analysis a necessity. A major problem presented by the use of a fractional-factorial array was confounding of variable effects. This created uncertainty in the determination of optimal decision and decision-dependent variable values. Another area requiring further study is the method by which the three-level fractional-factorial array was generated. The use of a Latin cube in this exercise was based on a single reference with no explanation as to the method of use.

The use of statistically designed experimental arrays provides a logical and efficient approach to the formulation and execution of sensitivity analyses. Additional work is required in assessing the statistical validity of array designs for specialized applications. One promising avenue of investigation is the use of this technique for sensitivity analysis of a probabilistic model followed by reduction of the model into an empirical equation via multiple regression.

7.0 SUMMARY

Survival and growth in the increasingly competitive world of manufacturing requires the ability to adapt quickly to changes in the marketplace. Risks associated with innovative products, organizational structures, and marketing strategies can be mitigated with the use of computer simulations used to predict the outcome of a given course of action. A computer simulation is especially valuable in providing a model that can be manipulated to determine the most appropriate course of action in light of uncertain market conditions. In the current study, an advanced composite material manufacturing operation was modeled using a computer simulation to determine the effect of a radical change in both organizational structure and marketing strategy on profitability. The model was complicated by a number of randomly-varying parameters internal and external to the manufacturing operation which influenced that profitability. Model manipulation, or sensitivity analysis, was performed to identify the organizational structure with the greatest probability of achieving high profitability.

The manufacturing operations were modeled as a series of departments each consisting of a waiting queue and a service center with probabilistic rejection/rework frequencies. Customer orders for manufactured components arrived on a random time basis. Raw material inventory accounting included randomly-generated material consumption quantities for each order, random raw material delivery times, specified order levels and order quantities, and a finite shortage cost based on a premium for emergency procurement. Other costs tracked by the model included raw material unit, procurement, and holding costs, department labor and capital costs, and order shipping costs. Revenue was generated in the model with each order shipped according to a formula which included a large sales price discount for late-order shipment. All cost elements were used to calculate the manufacturing operation profitability based on a modified return-on-investment (ROI) effectiveness function.

The model sensitivity analysis was formulated as a statistically-designed experiment in which decision variables and decision-dependent variables were varied according to a three-level, fractional-factorial format. A number of decision-independent variables were made to vary in a random manner in order to represent the uncertainties present in the real world business environment. For each test condition, defined as a set of decision and decision-dependent variables in the fractional-factorial array, ten separate computer simulation runs were performed. The mean and standard deviation of ROI were then calculated assuming a normal distribution for the ten simulation runs at each test condition. Selection of the optimal test condition was based on achieving the highest probability of exceeding a specified baseline ROI. This optimality evaluation was repeated using a 99-percent confidence limit on the ROI means.

Results of the model sensitivity analysis indicated that several of the test conditions (variable sets) achieved ROI levels in excess of the specified baseline requirement. In addition, credibility of the model was verified by comparing model output (e.g., inventory-time profile) with expected output. This provided confidence that the manufacturing operation being modeled could be modified to achieve a high level of profitability.

Two significant shortfalls in the sensitivity analysis provided direction for further improvement. The generation and use of a fractional-factorial designed experiment format raised the possibility that the selected variable set was not optimal. This uncertainty was due primarily to confounding of the effects of the decision variables. One additional refinement not addressed in the existing sensitivity analysis is the evaluation of alternative sequencing or dispatching rules for order flow into the various departments. Establishing a priority for specific orders in the waiting queues may help eliminate isolated late order deliveries. The other shortfall was due to not using a discounted cash flow basis for evaluating the profitability of alternative variable sets. It is suggested that performing an initial sensitivity analysis using only two levels per variable would isolate critical variables for subsequent evaluation in a more focused three-level sensitivity analysis. Despite these shortfalls, the study was a success by: (1) creation of a computer model that provided a reasonable representation of a manufacturing operation; and (2) demonstration of a designed-experiment format for performing sensitivity analysis and optimization.

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APPENDIX A

```
'APPENDIX A

'THIS PROGRAM IS A SIMULATION OF A FANCIFUL COMPANY CALLED EFECT,INC.
'THE COMPANY IS MODELED AS A SINGLE STREAM FLOW OF PRODUCT ORDERS
'THROUGH SIX SEQUENTIAL DEPARTMENTS.



CLS
SCREEN 2
OPEN "SHIPPED.TXT" FOR OUTPUT AS #1
OPTION BASE 1

'SIMULATION RUN DURATION
DAYS& = 1095
DIM NO%(9)
DIM NA%(15)
DIM PROFIT&(27, 10)
DIM INVENT%(1500)
DIM DELIV%(1500)
DIM FIN%(500)
DIM MCOST%(500)
DIM ORDER%(500, 15)
DIM COUNTER%(500, 15)
DIM SUMER%(500, 15)
DIM SERVA%(15)
DIM REJ!(15)
DIM SUM%(500)
DIM CA%(15)
DIM CAP&(15)
DIM PRICE&(500)


FOR B% = 1 TO 10
FOR T% = 1 TO 27
READ NO%(1), NO%(2), NO%(3), NO%(4), NO%(5), NO%(6), NO%(7), NO%(8), NO%(9)

PRINT "CONDITION"; T%; ",TRIAL"; B%


NA%(1) = 3 + NO%(1)
NA%(3) = 3 + NO%(2)
NA%(5) = 3 + NO%(3)
NA%(7) = 14 + 2 * NO%(4)
NA%(9) = 2 + NO%(5)
NA%(11) = 2 + NO%(6)
D% = 1000 + 100 * NO%(7)
ORDL% = 900 + 100 * NO%(8)
VEST% = 2 + NO%(9)
```

APPENDIX A (CONT'D)

```
CA%(1) = 400
CA%(3) = 400
CA%(5) = 1000
CA%(7) = 400
CA%(9) = 400
CA%(11) = 300
CAP&(1) = 2000
CAP&(3) = 2000
CAP&(5) = 50000
CAP&(7) = 10000 * VEST%
CAP&(9) = 5000
CAP&(11) = 2000
REJ!(2) = .01
REJ!(4) = .02
REJ!(6) = .04
REJ!(8) = .02 / VEST%
REJ!(10) = .02
REJ!(12) = .01
AA% = 1
BB% = 1
SUMM% = 0
CHOLD& = 0
CLABOR& = 0
CCAP& = 0
CMATL& = 0
INVORD% = 0
ORD% = 0
INVOICE& = 0
SET% = 0
FOR Q% = 1 TO 500
 MCOST%(Q%) = 0
 FIN%(Q%) = 0
 SUM%(Q%) = 0
  FOR W% = 1 TO 15
   SERVA%(W%) = 0
   ORDER%(Q%, W%) = 0
   SUMER%(Q%, W%) = 0
  NEXT W%
NEXT Q%

MONTH% = 0

FOR P% = 1 TO DAYS&
 INVENT%(P%) = 0
 DELIV%(P%) = 0
NEXT P%
INVENT%(1) = D%
V% = 1
FOR Z% = 1 TO DAYS&
```

APPENDIX A (CONT'D)

```
'GENERATION OF ORDERS AND RANDOM SERVICE TIMES
EM! = RND
IF EM! < .285714 THEN
  ORD% = ORD% + 1
  COUNTER%(ORD%, 2) = INT(3.5 + ((-.5 * LOG(RND)) ^ .5) * AA%)
  COUNTER%(ORD%, 4) = INT(5 + RND * 5)
  COUNTER%(ORD%, 6) = INT(4 + RND * 5)
  COUNTER%(ORD%, 8) = INT(35 + ((-8 * LOG(RND)) ^ .5) * BB%)
  COUNTER%(ORD%, 10) = INT(2 + RND * 3)
  COUNTER%(ORD%, 12) = INT(3 + RND * 3)
  COUNTER%(ORD%, 7) = INT(50 + RND * 51)
  AA% = -AA%
  BB% = -BB%
  ORDER%(ORD%, 1) = 1
  SUMER%(ORD%, 1) = 1
END IF

'ORDERING RAW MATERIAL
IF Z% > V% THEN
 IF INVENT%(Z%) < ORDL% THEN
  V% = Z% + 30 + RND * 21
  DELIV%(V%) = D%
  INVORD% = INVORD% + 1
 END IF
END IF

'PROCEEDING THROUGH THE SIX DEPARTMENTS
FOR Y% = 1 TO 11 STEP 2
 X% = Y% + 1
 W% = Y% + 2
 'DEPARTMENT QUEUE
  FOR M% = 1 TO ORD%
   IF SERVA%(Y%) < NA%(Y%) THEN
    IF SUMER%(M%, Y%) = 1 THEN
     SUMER%(M%, Y%) = 0
     SUMER%(M%, X%) = 1
     SERVA%(Y%) = SERVA%(Y%) + 1
    END IF
   END IF
   ORDER%(M%, Y%) = ORDER%(M%, Y%) + SUMER%(M%, Y%)
  NEXT M%
```

APPENDIX A (CONT'D)

```
 'DEPARTMENT OPERATIONS
  FOR L% = 1 TO ORD%
   IF SUMER%(L%, X%) = 1 THEN
    IF ORDER%(L%, X%) >= COUNTER%(L%, X%) THEN
     SUMER%(L%, X%) = 0
     SUMER%(L%, W%) = 1
     SERVA%(Y%) = SERVA%(Y%) - 1
      IF Y% = 7 THEN
       IF COUNTER%(L%, 7) < INVENT%(Z%) THEN
        MCOST%(L%) = MCOST%(L%) + 100 * COUNTER%(L%, 7)
        INVENT%(Z%) = INVENT%(Z%) - COUNTER%(L%, 7)
        ELSE
        MCOST%(L%) = MCOST%(L%) + 200 * COUNTER%(L%, 7)
       END IF
      END IF
      EMM! = RND
       IF EMM! < REJ!(X%) THEN
        ORDER%(L%, X%) = 0
        COUNTER%(L%, X%) = COUNTER%(L%, X%) * 2
        SUMER%(L%, X%) = 1
        SUMER%(L%, W%) = 0
        SERVA%(Y%) = SERVA%(Y%) + 1
       END IF
     END IF
   END IF
   ORDER%(L%, X%) = ORDER%(L%, X%) + SUMER%(L%, X%)
 NEXT L%

NEXT Y%

R% = Z% + 1
'RECEIVING RAW MATERIAL INVENTORY
INVENT%(R%) = INVENT%(Z%) + DELIV%(Z%)


NEXT Z%

'BEGIN COST ACCOUNTING
FOR YY% = 1 TO 11 STEP 2
 CCAP& = CCAP& + NA%(YY%) * CAP&(YY%)
 CLABOR& = CLABOR& + NA%(YY%) * CA%(YY%)
NEXT YY%

CSTAFF& = CLABOR& * DAYS&

CORDER& = INVORD% * 1000

SHIP& = 0
```

APPENDIX A (CONT'D)

```
FOR LL% = 1 TO ORD%
 CMATL& = CMATL& + MCOST%(LL%)
  IF ORDER%(LL%, 12) >= COUNTER%(LL%, 12) THEN
   SHIP& = SHIP& + 1
   FIN%(LL%) = 1
  END IF
NEXT LL%

FOR ZZ% = 1 TO DAYS&
 CHOLD& = CHOLD& + INVENT%(ZZ%)
NEXT ZZ%

CSHIP& = SHIP& * 200

TCOST& = CCAP& + CORDER& + CMATL& + CHOLD& + CSHIP& + CSTAFF&

ACOST& = TCOST& / SHIP&
PRINT "TEST CONDITION"; T%; ",TRIAL"; B%
PRINT "UNITS SHIPPED IN"; DAYS&; "DAYS="; SHIP&
PRINT "TOTAL OPS COST="; TCOST&
PRINT "UNIT COST="; ACOST&
FOR I% = 1 TO ORD%
 IF FIN%(I%) = 1 THEN
  FOR J% = 1 TO 12
   SUM%(I%) = SUM%(I%) + ORDER%(I%, J%)
  NEXT J%
   IF SUM%(I%) > 60 THEN
    SET% = SUM%(I%) - 60
    ELSE
    SET% = 0
   END IF
  PRICE&(I%) = COUNTER%(I%, 7) * 100 + 90000 - 20 * (SET% ^ 2)
  INVOICE& = INVOICE& + PRICE&(I%)
  SUMM% = SUMM% + SUM%(I%)
 END IF
NEXT I%
AVG% = SUMM% / SHIP&
PRINT "AVERAGE FLOWTIME PER SHIPPED ORDER="; AVG%
PRINT "INVOICES FOR YEAR ="; INVOICE&
PROFIT&(T%, B%) = INVOICE& - TCOST&
PRINT "FOR CONDITION"; T%; ",TRIAL"; B%; "YEARS PROFIT ="; PROFIT&(T%, B%)
PRINT " "
PRINT #1, T%, B%, PROFIT&(T%, B%), TCOST&, SHIP&

NEXT T%

RESTORE

NEXT B%
```

APPENDIX A (CONT'D)

```
'EXPERIMENTAL ARRAY
DATA 1,1,1,0,1,1,0,0,-1
DATA 1,1,0,0,0,0,-1,0,1
DATA 1,1,-1,0,-1,-1,1,0,0
DATA 1,0,1,-1,0,0,1,-1,-1
DATA 1,0,0,-1,-1,-1,0,-1,1
DATA 1,0,-1,-1,1,1,-1,-1,0
DATA 1,-1,1,1,-1,-1,-1,1,-1
DATA 1,-1,0,1,1,1,1,1,1
DATA 1,-1,-1,1,0,0,0,1,0
DATA 0,1,1,-1,0,-1,1,1,1
DATA 0,1,0,-1,-1,1,0,1,0
DATA 0,1,-1,-1,1,0,-1,1,-1
DATA 0,0,1,1,-1,1,-1,0,1
DATA 0,0,0,1,1,0,1,0,0
DATA 0,0,-1,1,0,-1,0,0,-1
DATA 0,-1,1,0,1,0,0,-1,1
DATA 0,-1,0,0,0,-1,-1,-1,0
DATA 0,-1,-1,0,-1,1,1,-1,-1
DATA -1,1,1,1,-1,0,-1,-1,0
DATA -1,1,0,1,1,-1,1,-1,-1
DATA -1,1,-1,1,0,1,0,-1,1
DATA -1,0,1,0,1,-1,0,1,0
DATA -1,0,0,0,0,1,-1,1,-1
DATA -1,0,-1,0,-1,0,1,1,1
DATA -1,-1,1,-1,0,1,1,0,0
DATA -1,-1,0,-1,-1,0,0,0,-1
DATA -1,-1,-1,-1,1,-1,-1,0,1
```

APPENDIX B

```
'APPENDIX B

'THIS PROGRAM USES APPENDIX A COMPUTER PROGRAM DATA
'TO CALCULATE MEAN ROI, ROI STANDARD DEVIATION,
'TEST CONDITION P-VALUE, AND TO CALCULATE THE
'AVERAGE EFFECT OF EACH VARIABLE
'LEVEL WITH RESPECT TO P-VALUE



CLS
OPTION BASE 1
SCREEN 2

'OPEN OUTPUT FILE
OPEN "WINNER.TXT" FOR OUTPUT AS #2

DIM PROFIT&(30, 12)
DIM APROFIT&(30)
DIM SPROFIT&(30)
DIM TCOST&(30, 12)
DIM SHIP&(30, 12)
DIM ROI!(30, 12)
DIM AROI!(30)
DIM SROI!(30)
DIM BROI!(30)
DIM SUMP&(30)
DIM SUMR#(30)
DIM A%(30, 10)
DIM SUMMER!(30)
DIM CAL!(10, 5)

'OPEN APPENDIX A PROGRAM DATA FILE
OPEN "SHIPPED.TXT" FOR INPUT AS #1

'CALCULATE ROI'S AND MEAN ROI
FOR B% = 1 TO 10
 FOR T% = 1 TO 27
  INPUT #1, COND%, ITER%, PROFIT&(T%, B%), TCOST&(T%, B%), SHIP&(T%, B%)
  APROFIT&(T%) = APROFIT&(T%) + PROFIT&(T%, B%) / 10
  ROI!(T%, B%) = 100 * .5 * PROFIT&(T%, B%) / TCOST&(T%, B%)
  AROI!(T%) = AROI!(T%) + ROI!(T%, B%) / 10
 NEXT T%
NEXT B%

'CALCULATE ROI STANDARD DEVIATION
FOR I% = 1 TO 27
 FOR J% = 1 TO 10
  SUMR#(I%) = SUMR#(I%) + ((ROI!(I%, J%) - AROI!(I%)) ^ 2)
 NEXT J%
NEXT I%

FOR K% = 1 TO 27
 SROI!(K%) = (SUMR#(K%) / 9) ^ .5
 AAROI! = AAROI! + AROI!(K%) / 27
 BROI!(K%) = AROI!(K%) - (2.821 * SROI!(K%) / 3.1627)
NEXT K%
```

APPENDIX B (CONT'D)

```
'CALCULATE P-VALUE
FOR L% = 1 TO 27
 EXX! = 20
 SUMMER! = 0
 FOR M% = 1 TO 1000
  EXX! = EXX! + .04
  FUNCT! = (1 / (SROI!(L%) * 2.506628)) * EXP(-((EXX! - BROI!(L%)) ^ 2) / (2 * (
SROI!(L%) ^ 2)))
  SUMMER!(L%) = SUMMER!(L%) + FUNCT!. / 25
  DOG! = 150 - FUNCT! * 300
  XX! = (EXX! - 20) * 15
  PSET (XX!, DOG!)
 NEXT M%
 LPRINT L%, SUMMER!(L%)
 CLS
NEXT L%

'CALCULATE AVERAGE EFFECT OF EACH ~~DESIGN~~ VARIABLE LEVEL
FOR N% = 1 TO 27
 FOR O% = 1 TO 9
  READ A%(N%, O%)
  SELECT CASE A%(N%, O%)
   CASE -1
    CAL!(O%, 1) = CAL!(O%, 1) + SUMMER!(N%) / 9
   CASE 0
    CAL!(O%, 2) = CAL!(O%, 2) + SUMMER!(N%) / 9
   CASE 1
    CAL!(O%, 3) = CAL!(O%, 3) + SUMMER!(N%) / 9
  END SELECT
 NEXT O%
NEXT N%

FOR P% = 1 TO 9
 CON! = 0
 FOR Q% = 1 TO 3
  IF CAL!(P%, Q%) > CON! THEN
   BEST% = Q% - 2
  END IF
   CON! = CAL!(P%, Q%)
 NEXT Q%
 LPRINT "FOR VARIABLE"; P%; "THE BEST SETTING IS"; BEST%
 PRINT #2, P%, CAL!(P%, 1), CAL!(P%, 2), CAL!(P%, 3)
NEXT P%
```

APPENDIX B (CONT'D)

```
DATA 1,1,1,0,1,1,0,0,-1
DATA 1,1,0,0,0,0,-1,0,1
DATA 1,1,-1,0,-1,-1,1,0,0
DATA 1,0,1,-1,0,0,1,-1,-1
DATA 1,0,0,-1,-1,-1,0,-1,1
DATA 1,0,-1,-1,1,1,-1,-1,0
DATA 1,-1,1,1,-1,-1,-1,1,-1
DATA 1,-1,0,1,1,1,1,1,1
DATA 1,-1,-1,1,0,0,0,1,0
DATA 0,1,1,-1,0,-1,1,1,1
DATA 0,1,0,-1,-1,1,0,1,0
DATA 0,1,-1,-1,1,0,-1,1,-1
DATA 0,0,1,1,-1,1,-1,0,1
DATA 0,0,0,1,1,0,1,0,0
DATA 0,0,-1,1,0,-1,0,0,-1
DATA 0,-1,1,0,1,0,0,-1,1
DATA 0,-1,0,0,0,-1,-1,-1,0
DATA 0,-1,-1,0,-1,1,1,-1,-1
DATA -1,1,1,1,-1,0,-1,-1,0
DATA -1,1,0,1,1,-1,1,-1,-1
DATA -1,1,-1,1,0,1,0,-1,1
DATA -1,0,1,0,1,-1,0,1,0
DATA -1,0,0,0,0,1,-1,1,-1
DATA -1,0,-1,0,-1,0,1,1,1
DATA -1,-1,1,-1,0,1,1,0,0
DATA -1,-1,0,-1,-1,0,0,0,-1
DATA -1,-1,-1,-1,1,-1,-1,0,1
```

APPENDIX C

```
'APPENDIX C

'THIS PROGRAM USES APPENDIX A COMPUTER PROGRAM DATA
'AND GENERATES CUBIC SPLINE CURVES
'TO FIT PROGRAM COST PLOTS




CLS
OPTION BASE 1
SCREEN 2

'OPEN APPENDIX A PROGRAM DATA FILE
OPEN "COST.TXT" FOR INPUT AS #1

DIM PROFIT&(5, 15)
DIM TCOST&(5, 15)
DIM SHIP&(5, 15)
DIM AVG%(5, 15)
DIM ACOST&(5, 15)
DIM AVCOST&(15)
DIM Y&(15)
DIM T%(15)
DIM H%(15)
DIM B!(15)
DIM U!(15)
DIM V!(15)
DIM Z!(15)
DIM FUN!(15)
DIM VCOST&(15)

'CALCULATES AND SCALES OPERATING COST AND TOTAL INVOICE DATA
FOR I% = 1 TO 3
 FOR J% = 1 TO 11
  INPUT #1, A%, T%, BB%, PROFIT&(I%, J%), TCOST&(I%, J%), SHIP&(I%, J%), AVG%(I%
, J%), ACOST&(I%, J%)
  AVCOST&(J%) = AVCOST&(J%) + TCOST&(I%, J%) / 3
  VCOST&(J%) = VCOST&(J%) + (TCOST&(I%, J%) + PROFIT&(I%, J%)) / 3
 NEXT J%
NEXT I%

RD% = 2

FOR RR% = 1 TO 2

FOR K% = 1 TO 11
 Y&(K%) = 190 - INT(AVCOST&(K%) / 200000)
 T%(K%) = 5 + 50 * K%
 CIRCLE (T%(K%), Y&(K%)), RD%
NEXT K%
```

APPENDIX C (CONT'D)

```
'SPLINE ROUTINE
FOR L% = 1 TO 10
 H%(L%) = T%(L% + 1) - T%(L%)
 B!(L%) = 6 * (Y&(L% + 1) - Y&(L%)) / H%(L%)
NEXT L%

U!(2) = 2 * (H%(1) + H%(2))
V!(2) = B!(2) - B!(1)

FOR M% = 3 TO 10
 U!(M%) = 2 * (H%(M%) + H%(M% - 1)) - (H%(M% - 1) ^ 2) / U!(M% - 1)
 V!(M%) = B!(M%) - B!(M% - 1) - (H%(M% - 1) * V!(M% - 1) / U!(M% - 1))
NEXT M%

Z!(11) = 0
Z!(1) = 0

FOR N% = 10 TO 2 STEP -1
 Z!(N%) = (V!(N%) - H%(N%) * Z!(N% + 1)) / U!(N%)
NEXT N%

FOR P% = 1 TO 10
 FOR R% = 1 TO 51 STEP 10
  X% = 4 + P% * 50 + R%
  FUN!(P%) = (Z!(P% + 1) / (6 * H%(P%))) * ((X% - T%(P%)) ^ 3) + (Z!(P%) / (6 *
H%(P%))) * ((T%(P% + 1) - X%) ^ 3) + ((Y&(P% + 1) / H%(P%)) - (Z!(P% + 1) * H%(P
%) / 6)) * (X% - T%(P%)) + ((Y&(P%) / H%(P%)) - (Z!(P%) * H%(P%) / 6)) * (T%(P%
+ 1) - X%)
  PSET (X%, FUN!(P%))
 NEXT R%
NEXT P%

'PLOT FORMAT
LINE (5, 190)-(605, 190)
LINE (5, 190)-(5, 40)
LINE (5, 40)-(605, 40)
LINE (605, 40)-(605, 190)
CIRCLE (100, 60), 2
CIRCLE (100, 80), 4

FOR Q% = 5 TO 605 STEP 50
 LINE (Q%, 190)-(Q%, 195)
NEXT Q%

FOR QQ% = 190 TO 40 STEP -10
 LINE (5, QQ%)-(0, QQ%)
NEXT QQ%

FOR O% = 1 TO 11
 AVCOST&(O%) = VCOST&(O%)
NEXT O%

RD% = 4

NEXT RR%
```