AN ABSTRACT OF THE THESIS OF

Sabah Randhawa for the degree of Master of Science in Industrial Engineering presented on August 15, 1980.

Title: A Methodology for the Economic Evaluation of Centralized Versus Decentralized Automated Component Insertion.

Abstract Approved: Redacted for Privacy
Dr. Edward D. McDowell

Productivity gains in the manufacturing sector have generally been credited to investments in production facilities that supplemented or replaced manual labor. Insertion of circuit boards is a key activity in the electronics industry. Improvements in productivity of circuit board manufacture may be achieved by replacing manual component insertion with automatic machine insertion. However, automatic insertion requires high capital expenditure; the capital must be invested in production alternatives that will result in the largest productivity improvement for every dollar invested. A critical decision regarding capital investment in component insertion is centralized versus decentralized insertion.

This study is primarily concerned with the problem of evaluating the economic feasibility of three production alternatives for circuit board manufacture--centralized production, in which all manufacturing operations are performed at one location; decentralized production, in which each business unit has an independent production cell; and satellite production, which uses a mixed production strategy whereby machine insertion is centralized but all other operations involved are decentralized.

The approach used in this study is to examine the different cost

parameters involved in circuit board manufacture and identify those factors which will differ significantly for the three production alternatives. Procedures are developed to estimate these cost parameters. The dollar values so obtained are then reduced to an annual worth basis for comparison purposes.

The methodology developed is then applied to analyze this problem at Tektronix, Incorporated. Based on the cost factors quantified in this study, the analysis showed that centralized circuit board manufacture results in the least capital expenditure, smaller operating and maintenance costs, and higher machine and manpower utilization.

A Methodology for The Economic Evaluation of Centralized Versus Decentralized Automated Component Insertion

by

Sabah Randhawa

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Completed August 15, 1980

Commencement June 1981

APPROVED:

Redacted for Privacy

Assistant Professor of Industrial Engineering in charge of major

Redacted for Privacy

Head of Department of Industrial and General Engineering

Redacted for Privacy

Dean of Graduate School

Date thesis is presented August 15, 1980

Typed by Sherry Scales for Sabah Randhawa.

ACKNOWLEDGEMENTS

My thanks are due to all of the people at Tektronix, Incorporated whom I consulted during the course of this study for their help and cooperation. I would especially like to thank Mr. Salahud-Din Faruqui for proposing this study and for aiding in the data collection.

Appreciation is extended to Dr. James L. Riggs whose interest in the subject provided valuable suggestions. Also, to Gifford L. Martin for his recommendations for improving the form of the text.

I am especially indebted to my major professor, Dr. Edward D. McDowell, who, during the course of this work, spent numerous hours discussing the various aspects and helped to develop a number of ideas into concrete thoughts.

Finally, I would like to thank Sherry Scales for her outstanding help in typing this thesis.

TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

LIST OF ILLUSTRATIONS

LIST OF TABLES

LIST OF TABLES (CONTINUED)

GLOSSARY OF TERMS

ARTWORK--an accurately scaled configuration used to produce a master pattern.

ATE (AUTOMATIC TESTING EQUIPMENT)--used for automatic testing of finished circuit boards. The functions that can be performed on ATE include testing for defective components, shorts and other build errors, and testing for group of components operating together.

AXIAL LEADS--leads coming out of the ends and along the axis of a resistor, capacitor, or other part, rather than out of the side.

CIRCUIT BOARD--sheets of plastic laminated together with a sheet or sheets of copper foil bonded to one or both sides. The laminated plastic provides a supporting and insulating medium for components and conductors in a form that is readily adaptable to machine handling and machine assembly.

CIRCUIT BOARD FABRICATION--the operation of punching or drilling holes and slots in circuit board and cutting board to required size and shape.

COMPONENT--an individual functional element in an electronic device which cannot be further reduced or divided without destroying its stated function, e.g., resistor, capacitor, diode, transistor.

COMPONENT DENSITY--the number of components per unit volume.

COMPONENT INSERTION--the process of attaching the electronic components onto the circuit board. Circuit board insertion can be performed either manually or through the use of automatic insertion machines.

COMPONENT, INSERTABLE: Insertable component refers to components that can be machine inserted.

CONNECTOR--used generally to describe all devices used to provide rapid connection/disconnection service for wire termination.

DISCRETE COMPONENT--a component which has been fabricated prior to its installation, e.g., resistor, capacitor, diode.

FLOW SOLDERING--a method of soldering printed circuit boards by moving them over a flowing wave of molten solder in a solder bath.

HAND ADDS--primarily a hand-insertion operation performed after soldering for components which have thermal and electrical properties that are affected by the high temperatures of the solder bath.

HARDWARE INSERTION--the process of inserting wire terminals or pins onto the circuit board.

INSPECTION--refers to manual, visual inspection for board quality and correct component installation.

INTEGRATED CIRCUIT--a functional structure fabricated on a single crystal by a batch process. An active semiconductor element called a chip serves as the functional part of an integrated circuit.

INTEGRATED CIRCUIT, DIP--DIP (dual in-line package) is the only form of integrated circuit being automatically inserted.

KIT PREPARATION (OR KIT PREP.)--involves the gathering of all components required for a board, cutting off and bending of components, and examining the components before assembly.

PART NUMBER--refers to the type of component. For example, a board with 20 partnumbers carries 20 different types of electronic components.

PART NUMBER, INSERTABLE--refers to component types which can undergo machine processing.

PRINTED CIRCUIT--the interconnection of a number of electrical components on a printed circuit board in one or more closed paths to perform a desired electrical or electronic function.

PRINTED CIRCUIT BOARD--refers to a fabricated circuit board.

PRINTED WIRING ASSEMBLY DRAWING--a document which shows the printed wiring base, the seperately manufactured components which are to be added to the base and any other information necessary to describe the joining of the parts to perform a specific function.

PRINTED WIRING LAYOUT--a sketch that depicts printed wiring substrate, the physical size and location of electronic components, and the routing of conductors that interconnect the electronic parts.

RADIAL LEAD--a lead extending out of the side of the component, rather than from the end.

SEQUENCE--output tape from the sequencer with electronic components arranged in an order which will minimize the cycle time of the insertion machine.

SEQUENCING--the operation in which a micro-computer controlled sequencing machine selects components from a number of input taped reels and retapes them in the required sequence to facilitate the insertion process.

SPAN--center-to-center distance between formed leads.

TRANSISTOR--an active semiconductor device capable of providing power amplification and having three or more terminals.

A METHODOLOGY FOR THE ECONOMIC EVALUATION OF CENTRALIZED VERSUS DECENTRALIZED AUTOMATED COMPONENT INSERTION

I. INTRODUCTION

Manufacturing is the backbone of the United States' economy, contributing $1,490 billion to the $2,109.6 billion 1978 Gross National Product. Over the past decade, the U. S. manufacturing sector has lost its world eminence. In 1978, the U. S. imported $8 billion more manufactured goods than it exported (McKee and McGurk, 1979). If the United States is to remain a leading manufacturing nation, it must improve its competitive position in world markets. This can only be achieved if the productivity of the manufacturing sector can be substantially improved.

Basic Concepts of Productivity

Productivity is the relationship between output of goods and services and the input of resources, human and non-human, used in the production process (Kendrick, 1979). The ratio may relate to the entire national economy, to an individual industry, or to a company or other producing organzation.

The volume of production depends upon both the volume of resources consumed and the efficiency with which they are consumed. When the ratio of output to total input increases, it indicates an increase in productive efficiency, or productivity. Over the long run, a productivity advance primarily reflects improvements in technology and the organization of production. In short periods, it also reflects changes in the rate of utilization of fixed plant and equipment and changes in labor efficiency.

There are other benefits that flow from increased productivity. It results in conservation or savings of scarce resources per unit of output; it helps to mitigate inflation by offsetting rising wage rates and other input prices; and it increases the international competitiveness of domestic production.

Productivity gains are primarily a result of capital investment. Productivity gains in the United States over the past 40 years have generally been credited to investments in production facilities that supplemented or replaced manual labor. According to Riggs (1978), future gains are expected from the same source, praticularly in industrial organizations.

Automatic Component Insertion

The electronics industry is an important sector of manufacturing. Any electronic device contains various types and configurations of electronic components. The most common method employed in fixing the components in electronic equipment is through the use of circuit boards. The process of attaching the components on the circuit board is called "circuit board insertion". Although the inserted circuit board is often a subassembly of a larger and considerably more complex electronic device, the direct costs associated with printed circuits will represent a major portion of the total variable manufacturing cost.

Component insertion on circuit boards can be done either manually or through the use of automatic insertion equipment. Manual component insertion requires considerable time to select the proper component, form component leads, insert the component into the circuit board, trim the leads, and then solder the leads. The manufacturing costs can be substantially reduced by automating the insertion process.

Automatic component insertion has proved to be economically advantageous whenever the volume and product mix justifies the investment. Estimates indicate four to five billion discrete devices and integrated circuits are automatically inserted annually in the United States, and that 30 percent to 40 percent of the printed circuits are produced automatically (Titlebaum, 1976).

Automatic insertion is employed for products with high volume and fairly constant mix of insertible components. Besides the benefits of lower manufacturing cost, expandable capacity, and reduced labor, automatic insertion also provides product reliability owing to the reproducibility of the manufacturing process. Improved reliability usually reduces total costs.

Productivity improvements in circuit board manufacture have resulted through replacement of manual insertion with automatic machine insertion. However, this requires high capital investment in insertion and testing equipment. Capital must be invested so as to yield the largest productivity improvement per dollar invested. A critical decision regarding capital investment in component insertion is centralized versus decentralized production. The decision is of particular importance to industries undergoing rapid expansion.

Tektronix, Incorporated

Tektronix, Incorporated (TEK), a leading manufacturer of oscilloscopes, is headquartered at Beaverton, Oregon. Tektronix designs, manufactures, and markets a broad range of test and measurement and information display products. Test and measurement products are used throughout the electronics, computer, communications, and medical industries. The mainstay of these product lines is the oscilloscope, the product for which the company is best known.

Although the oscilloscope is still TEK's principal test and measurement product, the company has applied advanced technologies to non-oscilloscope products, also. One such product is information display and computer graphics terminals. Information display products include graphic terminals for computers and computer peripherals. Computer graphics lets the user put information into pictorial form and is used in science, business, architectural and automotive design, and a wide array of other applications.

Problem Statement

A centralized machine insertion area with an annual insertion capacity of 40 million components supplies 30 to 35 percent of TEK's current printed circuit board (PCB) requirement. TEK, however, has been experiencing a growth rate averaging over 20 percent per annum over the past five years. Based on this 20 percent per annum forecasted growth rate, machine insertion requirements will exceed 300 million components per year by 1985. The current machine insertion capacity is insufficient to meet this increasing production requirement.

Currently, machine insertion only supplies one-third of the total board requirement. With labor rates increasing steadily due to inflation, it may be more economical to have only those boards hand-inserted which cannot undergo machine processing due to component size or shape limitations, or those which have a production volume so low as to make machine insertion uneconomical. Using this criterion for insertion, 85 percent of the printed circuit boards will have to be machine inserted. This will substantially increase machine insertion load.

Besides experiencing rapid growth, TEK has also been undergoing physical decentralization. Although the main facility is located at Beaverton, a number of new facilities have sprung up in Oregon and Washington. With distribution costs appearing to be a significant factor in the future, it may be more economical for the decentralized units to have independent production cells, which include provision for both machine and hand insertion. A critical decision which TEK now faces is that of centralized versus decentralized circuit board manufacture.

Alternatives

The increased component insertion requirement may be met by following one of three alternatives: (1) a centralized manufacturing facility which supplies the total TEK circuit board requirement, (2) decentralized production with each division having an independent production cell, or (3) by following a mixed production strategy whereby machine insertion is centralized but all other operations involved in PCB manufacture, such as hand-insertion, flow soldering, and inspection, are decentralized.

Centralized component insertion. In this concept, circuit boards are processed in a centralized insertion area which includes both machine and manual insertion. A process-type layout is envisioned for this system with similar machines located together. The advantages associated with this layout generally include better utilization of machines, fewer machines, and ease of supervision. An additional advantage in this type of arrangement is the possible application of a hierarchical computer control system which provides different independent levels of automation depending on the production requirement. Since the work flows through different work centers in batches, this type of production is usually associated with large in-process inventories.

Decentralized component insertion. In this arrangement, each division has a production cell with provision for machine and hand insertion. The advantage of such an arrangement is greater freedom in scheduling and little or no waiting time. On the other hand, the volume should be high enough to justify investment in machinery, otherwise, low utilization and high capital investment may result.

Centralized machine insertion/decentralized hand insertion. This alternative, also referred to as "satellite arrangement", preserves the present production arrangement--a centralized machine insertion area performing sequencing, component and hardware insertion with all other operations decentralized; expansion in capacity follows the existing production pattern. This type of arrangement may help in cutting down the high equipment investment required in decentralized production while, at the same time, eliminating the high risk involved in the distribution of finished circuit boards as in centralized production. It does, however, involve the additional cost of inspecting the boards after they are machine inserted. This inspection is eliminated in both centralized and decentralized production facilities since all operations are performed at the same location.

Objective and Scope of Study

This study is concerned with the problem of evaluating the economic feasibility of the three alternatives described previously: centralized insertion, decentralized insertion, and satellite production. While the methodology developed is primarily oriented toward solving this problem at Tektronix, the procedures described are general enough to be applicable to the analysis of any similar situation.

The complexity of the system makes it necessary to simplify the problem being considered as much as is practical. The study assumes a planning horizon of five years. The study covers all operations involved in PCB stuffing. These include automatic machine insertion, hardware insertion, hand insertion, flow soldering, and inspection. It does not cover board design and fabrication and generation of numeric control tapes and scheduling procedures, which are significant operations but beyond the scope of this study.

In order to keep the problem within manageable size, certain limiting assumptions have been made. Perhaps the most important of these is that the monetary unit is a constant value measure of worth, and inflationary effects can be ignored. This implicitly assumes that the alternatives under consideration and their cash flow streams are impacted nearly the same by inflation. The difference between alternatives remains proportionally the same whether the current value or future value of dollars is employed in the comparison. When discounting the future value to the present worth value, the discount rate used takes into account the increase due to both the time value of money and inflation (Estes, Turner, and Case, 1980; Riggs, 1980).

For the particular set of alternatives in this study, the difference in inventory cost is neglected. Inventory carrying costs are those costs which are directly attributable to the amount, type, and location of inventory carried and increase in direct proportion to increases in inventory on hand and the time for which the inventory items are held. The problems involved in evaluating the inventory costs at TEK are the absence of a consistent inventory policy and the nonavailability of both current and historical data on safety stocks carried.

An additional element of uncertainty in evaluation of inventory costs is added by the effects of inflation on inventory stocks. Under normal conditions, low buffer stocks are favored since it minimizes carrying costs and storage space. However, during periods of high inflation, it may be more economical to carry large stocks to guard against anticipated price increases.

Additional assumptions are made in evaluating capital cost. Its evaluation is based on existing equipment capacities and limitations and on current economic order quantity (EOQ) standards used by TEK. Equipment and manpower requirements are developed based on a five-day workweek, a 14-hour workday, and a 50-week year.

Approach

The procedure used in this study is outlined in the following steps:

1. Identify relevant cost factors which differ significantly for the alternatives being considered. PCB manufacture involves cost evaluations at different stages in the production process. Even though some of these individual costs may constitute a significant proportion of the total costs, variations between alternatives may be small enough for

these costs to be neglected. Only those cost parameters which vary substantially between alternatives are considered here.

2. Develop cost estimates for the factors identified in Step 1. This step involves model development for evaluating the cost parameters.

3. Perform discounted cash flow analysis to identify the best alternative. The cost values are reduced to an annual cost figure for each alternative for comparison purposes; the preferred alternative is the one with the least annual cost.

4. Determine the sensitivity of the selected alternative due to variability in the production growth rate. The analysis of this study uses an annual growth rate of 15 percent. A sensitivity analysis examines the effect of a change in production growth rate on the optimum alternative identified using a 15 percent annual growth rate.

This approach is developed in this study. It is then applied to analyze this problem at Tektronix, Incorporated.

II. BACKGROUND

Printed circuit board manufacture involves a number of operations that are summarized in the flow-chart below.

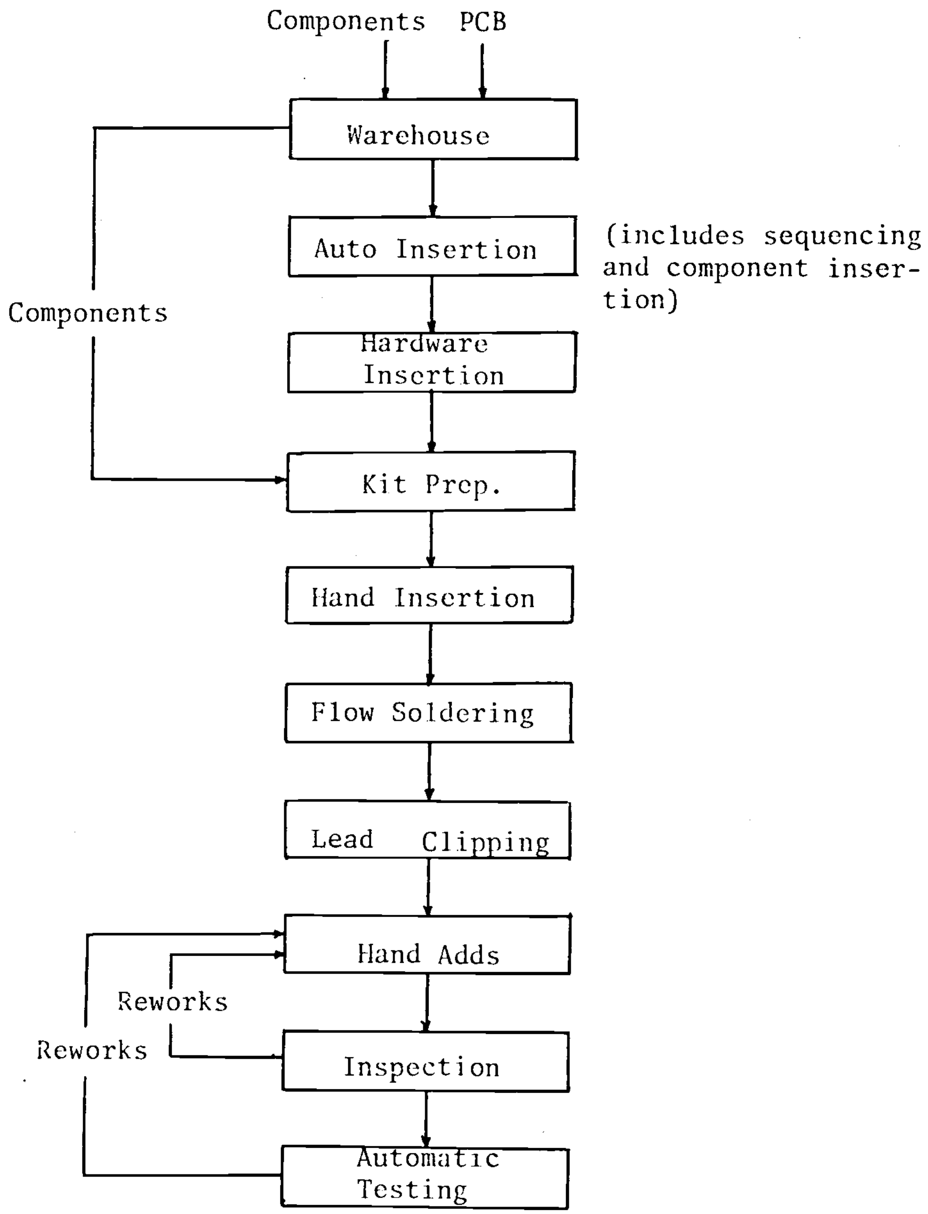


Figure 1. Flow-chart showing operations involved in PCB manufacture.

Circuit boards and electronic components serve as raw materials in the circuit board manufacturing system. Circuit boards have already been processed through the design and fabrication phases before being sent to the warehouse. Board fabrication involves the punching and drilling of holes in the circuit board and cutting the board to the required size or shape. The design phase serves as the basis for generating numeric control tapes for operation of the sequencers and component inserters.

Circuit Board Design Phase

Automatic equipment can insert components in single, double, or multilayer printed boards at speeds varying from several hundred to several thousand insertions per hour. The cost savings with automatic equipment depends heavily on board design. Very minor variations in component orientation, span (center-to-center distance between formed leads), and location can make a design desirable, undesirable, or impossible for automatic component insertion.

The printed circuit board design phase, as described by Wilkinson (1975), involves a schematic drawing which shows the components being used and their interconnecting paths. The next stage is the physical layout, usually on a printed circuit board. For this layout, a set of photographic masks are produced so that prototype printed circuit boards can be developed. Prototypes are then developed and tested and the modification process follows, if necessary, to correct any defects in the design.

During the design phase, components may have to be rearranged by the designer to satisfy requirements beyond the scope of any automatic placement program. Considerations for rearrangement might be: thermal, locating heat generating components far from other components or areas that might be sensitive to elevated temperatures; mechanical, either for ease of component insertion during manufacture or to prevent unbalanced concentrations of mass in certain spots; and for maintainability, in that the components most subject to replacement are easily accessible.

The system's automatic interconnection routines define circuit wiring paths between components. It may take several iteration cycles before satisfactory results are achieved. A routine is then used to minimize the path lengths of interconnections while retaining the electrical components.

Once the design is complete, a computer package produces final artwork, drawings for component placement, and numeric-controlled (N/C) tapes to run drilling machines for the boards. The final "snake-path" for the board is also used to generate the N/C tapes for the sequencing operation.

Sequencing

The automatic insertion of components on printed circuit boards requires that the taped components at the insertion machines input be in a predetermined order or sequence. The sequencing operation is performed on a micro-computer controlled sequencing machine that selects components from a number of input taped reels, each of which contains a unique component and retapes them in the required sequence. The sequencer removes the component from the proper reel and places it on a continuous tape strip, the strip winds onto another reel so that on completion of the sequencing, the operator can transport the take-up reel to the automatic component insertion machine.

Since hundreds of different types of components are used in the PCB's, this necessitates changes in the sequencer component and tooling set ups from board to board. These set up changes add labor to the cost of producing PCB's automatically and reduces the amount of available sequencer production time.

Richerson (1976) describes two methods which can be used to develop sequencer schedules for minimizing the extent of set up changes. In the first, a travelling salesman model, each tooling set up is analogous to a point in space. The number of component changes required to go from one set up or point to another is the distance between the points. The objective is to minimize the total distance travelled in visiting a given set of points. Any algorithm for solving a travelling salesman problem may be used to determine the best scheduling sequence.

An alternative approach to solving the sequencer scheduling problem is to develop a heuristic approach. For example, one simple heuristic is to schedule the PCB requiring the fewest component and tooling changes as the next one on the sequencer.

An additional feature on some sequencers is the capability of performing a verification test. This test has the capability of testing resitors, capacitors, diodes, or varistors. Internal standards which are provided by the computer cover the range of zero to ten megohms and from 10 picofarads to 100 microfarads for resistence and capitance testing, respectively (Bridges, 1977). The test ensures that the components at the machine's output are in the proper order and detects defective or missing components. The input program to the sequencer requires the sequence list, which defines the output sequence and the test message, which defines the test requirements for each component.

Component Insertion

The insertion machine takes the parts from the sequenced tape and mounts them on the PCB. The process of automatic component insertion requires a computer program to move the insertion machine X-Y table to the proper location, to remove a component from a reel, and to insert the component onto the board location. The most economical program minimizes the X-Y travel (Pericich, 1978).

The insertion system can be built in either of two configurations: in-line or pre-sequenced. In the pre-sequenced configuration, a sequencer first produces a sequenced reel which is then loaded onto a single insertion machine, which places all the components on a single board and then releases the board for the next operation.

The in-line method uses a large number of essentially identical machines, each of which inserts a single kind of component at a particular spot on the board. Components can be of any type, fed by reels, tubes, vibrating bowls, or any other suitable method. The machines are placed side-by-side in a long row, linked by a transfer mechanism. The board, placed at the start of the conveyor, works its way down the line, pausing at each machine which mounts its type of component in the designated places. Unlike the pre-sequenced inserter, in-line insertion does not require a pattern control program, which would tell the machine what the whole board looks like. When the board comes off at the end of the line, it is checked to ensure that it is fully populated with components and sent to the next operation.

The computer requirements for the two configurations are quite different (Freese, 1974). In the sequencer, the computer places each component on the moving band at the right time, so that it is the right distance behind the previous component. The computer, with the aid of mechanical switches, also detects when a component is missing before it should be taped into place on the output reel. The switch stops the machine and flashes a warning to the operator to replace the part manually.

When the sequenced components are inserted, the computer controls the horizontal movements of the board in two-dimensions to bring the proper insertion points under the head. The computer initiates a sequence that includes inserting the component, cutting and crumping the head, and repositioning the board for the next component.

The in-line method requires the computer to simultaneously control a number of insertion heads, as well as feed empty boards from an input stock into the conveyor, check that the board was fed, verify that the board was moved into position at each station, and check after the last station for the presence of all components.

The current mode of operation at TEK uses pre-sequenced insertion. This study will only be concerned with this type of insertion.

Hardware Insertion

The next operation, hardware or pin insertion, is performed automatically using terminal insertion machines. The wire terminals are provided on large reels in a continuous strip with the terminals connected to each other in the end-to-end configuration. This arrangement reduces the amount of scrap material and provides a more reliable method for feeding and insertion. Each insertion machine operates off of a paper tape on its own mini-computer.

Kit Preparation

The primary function of Kit Preparation (Kit Prep.) is to speed up circuit board assembly and reduce operator error involved in choosing wrong components. Kit Prep. involves the gathering of all components required for a board, cutting off and bending of components before assembly and examining components for any damage. The components, gathered in the form of a kit, are then stored, preferably in an automatic retrieval system, ready for use when required.

Hand Insertion

For machine insertion to be feasible, the boards must have a relatively high production volume and a sufficient number of machine insertable components to justify the high set up cost of the sequencer and the insertion machines. Boards that do not meet these requirements are hand-inserted. Furthermore, a number of components that cannot be machine inserted due to their size or shape are also hand-inserted.

Manual component insertion is economically advantageous for low insertable component densities and small lot sizes. Figure 2, taken from Titlebaum (1976), shows the price versus productivity of axial lead and dual-in-package insertion systems for comparison with hand insertion.

Semi-automatic and automatic machines are becoming more varied. Machines now have insertion rates ranging from 1,000 to 100,000 components per hour at prices from $6,000 to $500,000. Axial lead components, integrated circuits in dual-in-line packages, transistors, disc capacitors, connectors, and other devices can be inserted with this equipment.

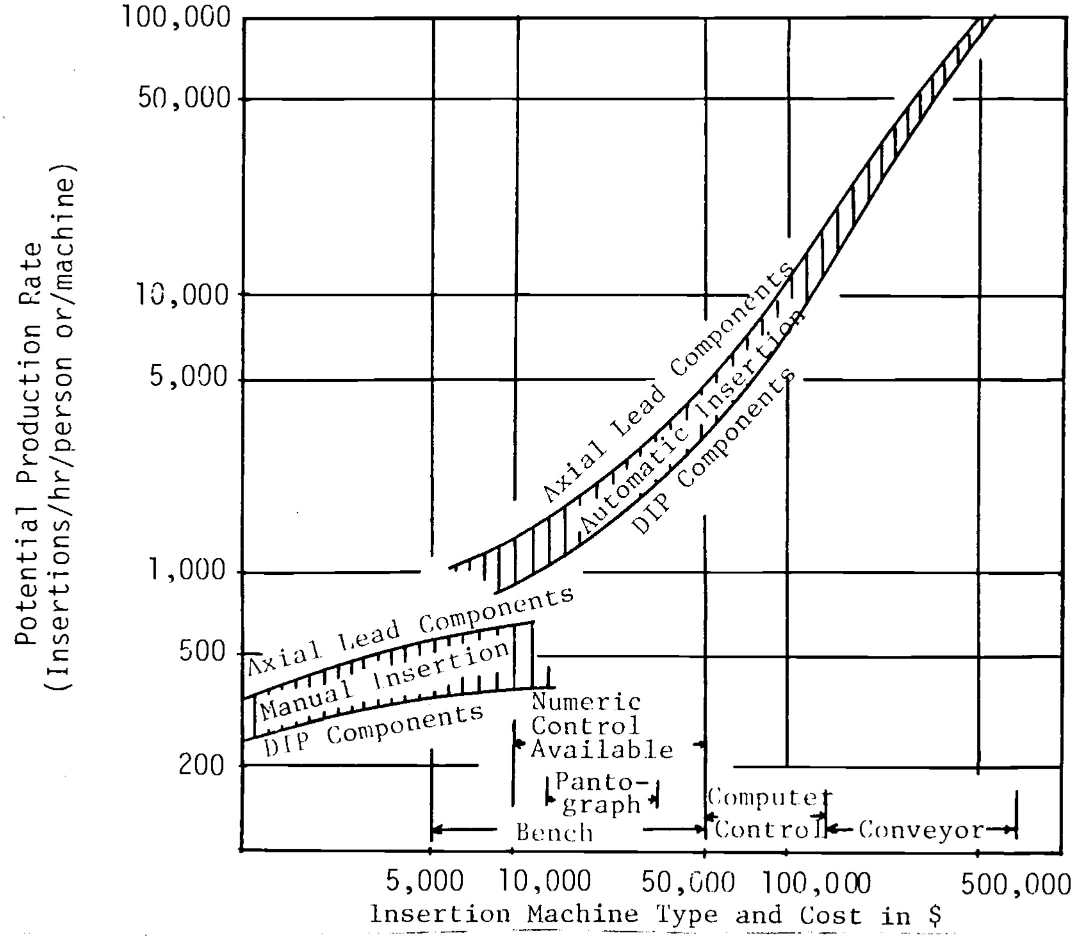


Figure 2. Potential production versus capital investment for manual and automatic component insertion. (Titlebaum, 1976)

The range of automatic insertion, as shown in Figure 2, varies from simple bench inserters, where an operator manually positions a board under the insertion head by means of a locating notch and activates the insertion cycle with a foot treadle; to pantograph inserters, in which a printed circuit board is mounted on an X-Y table that is positioned under the insertion head by the operator moving a stylus; to automatic sequencing and insertion and conveyor systems for high-volume in-line production.

Flow Soldering

Flow soldering is a continuous operation performed on machines called "electroverts". In this operation, a board is run through a flow solder bath and then an in-line cleaning system, which is part of the machine. The in-line cleaning system removes excess flux which may have adhered to the circuit board during the soldering process. Dried flux left on boards can cause arcing in high-voltage circuits and leakage in high-impedence circuits.

Hand Adds

Hand adds is primarily a hand insertion operation. Components whose electrical or thermal properties are affected by the high temperature in the flow soldering bath are hand-inserted at this stage and then hand-soldered.

Inspection, ATE

Inspection refers to manual visual inspection for board quality and correct component installation. Automatic testing equipment (ATE) is then used to automatically perform tests according to a programmed sequence. ATE reduces uncertainty and increases conformance to specifications.

There are two principle applications of ATE--incircuit and functional testing. Incircuit testing is used for testing individual components. Incircuit testing detects all shorts, build errors, and most faulty components. Incircuit testing finds multiple faults per pass and inexpensively accesses all modes of boards. The testing time for a good board or troubleshooting a faulty board is about one minute.

Functional ATE is used for testing functions, that is, a group of components operating together. It checks for the proper transfer function, that is, proper outputs for inputs provided. The mode access for this type of testing is quite expensive. It tests a good board in about ten seconds; however, troubleshooting of bad boards takes one to fifteen minutes, depending on board design and amount of operator assistance needed.

The type of testing equipment used depends largely on the quality of assembled boards. The best approach involves a combination of equipment.

PCB Manufacture at Tektronix, Incorporated

The current centralized machine insertion area which is supplying 30 to 35 percent of the company's current printed circuit board requirements houses three operations: sequencing, component insertion, and hardware insertion. The major inputs to this area consist of drilled circuit boards, components, and computer tapes for running the sequencers and insertion machines. The area currently has three sequencers, each capable of handling 80 components and an average production rate of 10,000 parts per hour per machine; seven component inserters with an insertion rate of 4,000 parts per hour per machine and three hardware inserters with an average capacity of 6,000 insertions per hour per machine.

Following machine insertion, boards are shipped to the division within the company for hand insertion, flow soldering, and inspection. Hand insertion is carried out as either in-line or bench insertion. In in-line insertion, each operator inserts one type of component as the board moves down the production line. In bench insertion, an operator inserts all components on a single board and then releases the board for the next operation. Currently, about 61 percent of the boards hand-inserted are bench inserted; 39 percent in-line inserted.

There are four divisions or business units in the company which utilize PCB's. These are Communications (COM), Information Display Division (IDD), Laboratory Instruments Division (LID), and Service Instruments Division (SID). Figure 3 summarizes the different products produced by these divisions as of Spring, 1980.

Criterion for Automatic Insertion

For machine insertion to be feasible, the boards must have a relatively high production volume and sufficient number of machine insertable components to justify the high set up cost of the sequencer and insertion machines. The following criterion, developed by the Manufacturing Engineering Systems (MES) Group at TEK, compares the cost of manual versus automatic insertion and is used in this study to decide the feasibility of boards for machine insertion.

Manual insertion:

TC_M = Total Cost ($/year) = (Board forecast per year x Components per board) x $0.01499 per component

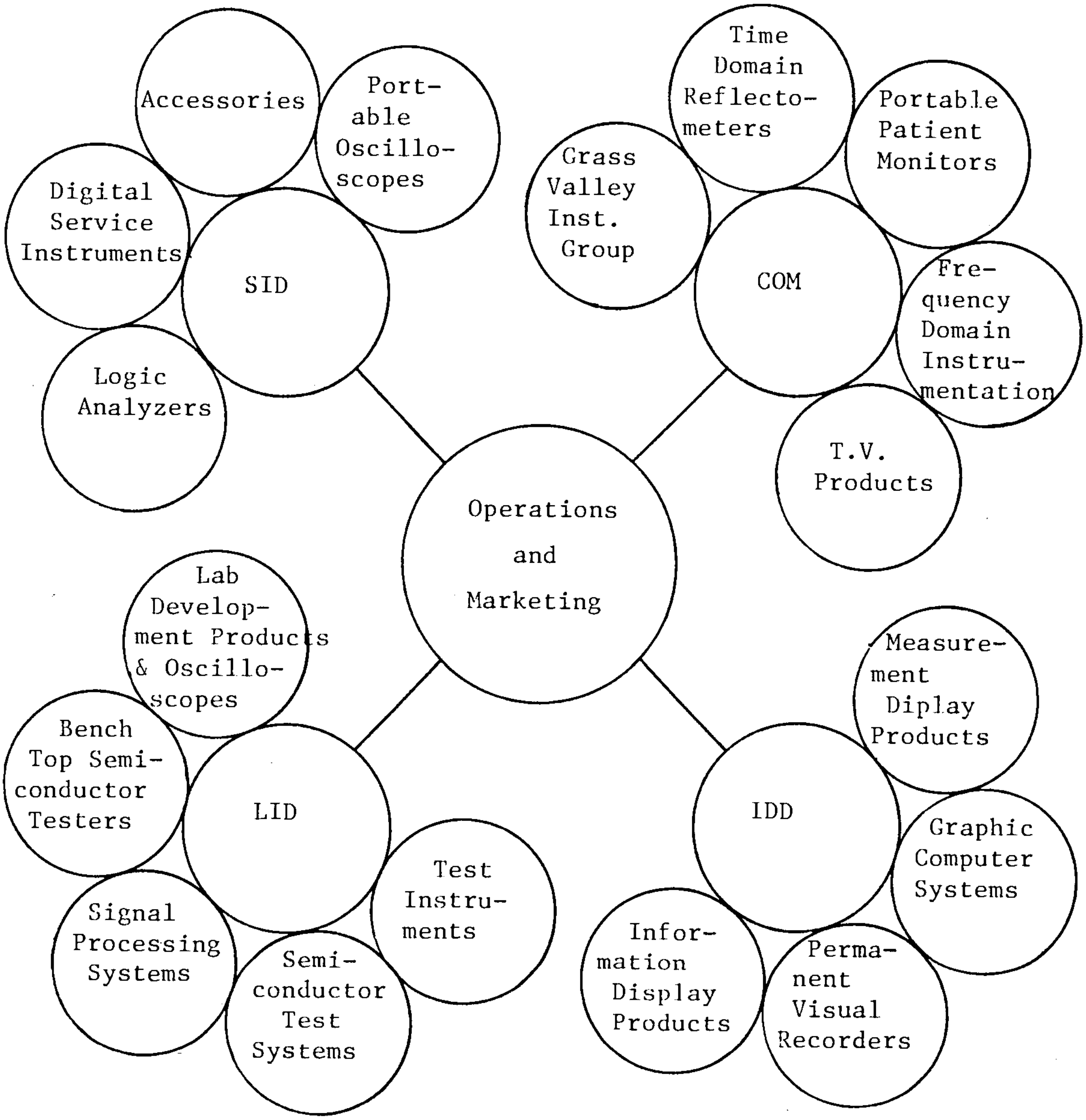


Figure 3. Business units at TEK as of Spring, 1980.

Automatic insertion:

$$
\begin{aligned}
TC_A = \text{Total Cost (\$/year)} = {} & 31.2 + (\text{Insertable components per board}) \times 0.044 && \text{Set up Cost} \\
& + (\text{Board forecast per year} \times \text{Insert components per board}) \times 0.00186 && \text{Fixed Cost} \\
& + 6.06 \times \{(\text{Board forecast per year} \times \text{Number of sequences}) \times 0.01283 && \\
& + (\text{Total components per board}) \times 0.0594 && \text{Variable Cost} \\
& + (\text{Total part numbers per board})^2 \times 0.0049\} &&
\end{aligned}
$$

Where, number of sequences = Integer $\frac{\text{Insertable part numbers}}{79}$

For each type of board, the costs of manual and automatic insertion are calculated based on the preceeding equations. If the cost of manual insertion is greater than the cost of automatic insertion, it is economically feasibel to machine insert the board; otherwise, manual insertion provides the least insertion cost.

III. MODEL DEVELOPMENT

The approach used in this study is to examine the different cost parameters involved in PCB manufacture and to identify those factors which will differ significantly between centralized, decentralized, and satellite modes of production; develop detailed procedure for estimating these cost parameters; and then to use some form of economic measure to decide between the three production alternatives. The economic measure used in this study is annual worth comparison.

Cost Factors in PCB Manufacture

Circuit board manufacture involves high capital investment in sequencing and insertion equipment. Even though all of the alternatives have the same production requirement to satisfy, the decentralized arrangement splits up manufacturing into a number of small production cells. This may result in a substantially lower machine utilization and, consequently, a much higher capital investment.

Next to capital investment, direct labor cost contributes a high proportion of overall manufacturing costs. Direct labor is required for operating the machines and for manual operations such as hand insertion and hand adds. Labor requirements between alternatives may not differ much for the manual operations, but may be higher for a decentralized facility in the case of machine operating labor because of the higher number of machines to be operated.

The nature of the electronics industry requires a stringent quality check of the finished circuit boards. This can be achieved through the use of automatic testing equipment. Again, the initial investment for testing equipment may be higher for decentralized and satellite production due to lower machine utilization. Satellite production also requires an additional inspection of machine-inserted circuit boards before they are distributed to the business units. This expense is not incurred in centralized and decentralized arrangements since all operations are performed at the same location.

Hiring and training expenses include the administrative costs associated with hiring and the cost of lost production while the operator is undergoing training. Hiring and training costs may vary substantially between alternatives, particularly if the labor turnover rate is different at different locations. The labor turnover rate at TEK is supposed to be confidential. Further, some of the business units are still in the process of physical decentralization so that the labor turnover rate at the new locations is yet to be established. Therefore, a common figure for turnover rate is used for all locations. The use of a constant turnover rate may result in a comparitively smaller cost difference than in actual practice.

Indirect labor cost and maintenance costs will vary between different alternatives. Indirect labor expense includes the cost of supervisory and support personnel. Maintenance expense includes the cost of maintenance staff and maintenance facilities. These expenses will be higher for decentralized and satellite arrangements because more facilities have to be managed for the same amount of output.

The cost involved in distributing circuit boards tends to favor decentralized production. It is assumed that the raw material warehouse is located along with the production facility, so that the cost of distributing raw materials is negligible. A centralized production facility will incur the cost of distributing finished circuit boards to the business units. A similar, though lesser, cost will be involved in satellite production where semi-finished boards are distributed to the business units. No distribution cost is involved in decentralized production since the boards are produced at the location where they are ultimately consumed.

The procedure for evaluating these cost parameters is discussed in the following sections. These are not the only cost parameters involved in PCB stuffing. Inventory cost is neglected because of the unavailability of current and historical data to develop an inventory model and because of the uncertainty introduced in inventory stock policy due to inflation. Development of computer scheduling and programming cost is beyond the scope of this study. There are still other intangibles which are difficult to quantify, though some of them may be important to consider in the final diecision-making process. Some of these intangible factors are:

1. Flexibility to meet changing conditions.
2. Ease of expansion without major disruption in the production process.
3. Ease of supervising/maintaining a common pool of programming and scheduling staff.
4. Changing trends in the policy of the top management.

Capital Cost

Automatic insertion involves a high capital expenditure for equipment. The main sources of investment are sequencers, component inserters, hardware inserters, flow soldering machines, and automatic testing equipment. The capital required for any particular type of equipment may be evaluated as the product of the number of units of that equipment required to meet the production requirement and the initial cost of one unit of the equipment. The initial cost includes the purchase price, freight cost, and installation cost. The total capital investment for an alternative is the sum of the investments required for the individual types of machines. In notational form, the total capital expenditure can be represented as

$$\sum_{j=1}^{n} E_j M_j$$

where, E_j = initial cost of one unit of machine-j

M_j = number of machines-j required to meet production requirements

n = number of types of machines, e.g., component inserters, hardware inserters, etc.

The number of machines required to meet the production requirements, M_j, may be evaluated using the standard formula given below (Francis and White, 1974). The formula is not used for the sequencer due to reasons which will be explained later.

$$U_j M_j = \sum_{i=1}^{N} \frac{P_{ij} T_{ij}}{C_{ij}} \quad , \text{ for all } j$$

where P_{ij} = desired production rate for product i on machine j, measured in pieces per production period

T_{ij} = production time for product i on machine j, measured in hours per piece

C_{ij} = number of hours in production period available for production of product i on machine j

U_j = utilization factor for machine j

N = number of products produced

The total production time (i.e., $\Sigma P_{ij} T_{ij}$) may be evaluated using two different methods. The first approach is to calculate the product of the production requirement and the insertion time per board for each type of board and then sum the product for all types of boards produced. The alternative approach is to estimate a mean insertion time based on a sample of boards and multiply it with the total board requirements to obtain the total production time. Since TEK is producing more than 1,000 different types of boards, enormous computations are involved in the first approach. The mean insertion time approach is, therefore, used to calculate the total production time for hardware inserters, flow soldering machines, and testing equipment.

The mean insertion time is estimated by taking a random sample of boards and calculating the weighted mean production time, $\overline{T}$, using the formula

$$\overline{T} = \frac{\sum_{i=1}^{n} w_i t_i}{\sum_{i=1}^{n} w_i}$$

where, w_i = number of boards-i required per annum

t_i = production time per board for board-i

n = sample size

A modified sampling plan is used to estimate the insertion time on the component inserter due to the nature of available insertion data. This modified sampling plan is discussed separately below in the section entitled "Component Inserter".

The production rate, P_{ij}, is obtained by translating the marketing forecast into the required production quantities. The future circuit board requirements are based on the current circuit board production and a growth rate of 15 percent per annum. This rate has been predicted by the marketing group at TEK.

The production period considered in this analysis is one year. The number of hours available in a production period, C_{ij}, are calculated based on a five-day workweek, 14 hours a day, and 50 weeks per year. The utilization factor, U_j, accounts for the downtime losses and idle time interferences and is evaluated using the maintenance records at TEK.

Component Inserter

A modified sampling plan is used for estimating the insertion time for component inserters due to the nature of the available insertion data. Currently, only about 30 to 35 percent of the total board requirement at TEK is machine inserted. However, the criterion for comparing manual versus automatic cost of insertion used in this study suggest that it is feasible to machine insert about 85 percent of the total boards. For boards that are currently being machine inserted, data on run and set up times is available as the machine times used for inserting these boards. For the potentially insertable boards, however, time date is not available. A regression model developed by the Manufacturing Engineering Systems Group at TEK was used to estimate these insertion times. The independent variables in this model are annual demand, number of insertable components per board, and number of insertable part numbers per board; the dependent variable is insertion time.

The insertion time per board depends on the number of insertable components per board and the volume of production. The insertion time for the two categories of boards--currently inserted and potentially insertable--may differ depending on the variations in production volumes and insertable components per board in the two categories. The mean insertion time for the two categories of boards are calculated separately and are then tested for any variations. If the two mean times are essentially the same, the data may be aggregated and a common forecasting model may be developed to predict the future board requirement. A difference in the two means implies separate treatment for the two classes of boards.

The production requirements and the insertion time per board are both random variables. A more rigorous approach may be do develop separate distributions for these two variables and then to estimate the insertion time from these distributions. The more simple procedure used here involves the determination of weighted averages of small samples of boards which are then used to determine an overall mean insertion time. By using the average insertion time as the estimator of the production time and by taking a large sample size, the distribution of the mean insertion time can be approximated by the normal distribution (Central Limit Theorem). Also, the use of this sampling plan provides a convenient method for calculating the sample variance. The variance is required for estimating the sample size and for conducting the t-test to test for variation in mean insertion times for the two categories of boards.

The mean insertion time is calculated by taking a number of random samples of equal size from the board population and calculating the mean insertion time for each sample, $\bar{t}_j$.

$$\bar{t}_j = \frac{\sum_{i=1}^{n} w_i t_i}{\sum_{i=1}^{n} w_i} \quad , \quad j = 1,2,\ldots N$$

where, w_i = number of boards-i required per annum, i=1,2,...n

t_i = insertion time per board for board-i, i=1,2,...n

n = subsample size

N = number of subsamples of size n

The overall mean insertion time, $\bar{\bar{t}}$, is then calculated using the expression

$$\bar{\bar{t}} = \frac{1}{N} \sum_{j=1}^{N} \bar{t}_j$$

The variance may now be calculated using the following formula

$$S_{\bar{t}}^2 = \frac{1}{N-1} \sum_{j=1}^{N} (\bar{t}_j - \bar{\bar{t}})^2$$

The sample variance is used for determining the number of samples required to meet the desired degree of precision, I, and confidence level, α (Snedecor and Chochran, 1978).

$$I = 2Z_{1-\alpha/2} \frac{S_{\bar{t}}}{\sqrt{N}}$$

from where

$$N = \frac{4Z_{1-\alpha/2}^2 S_{\bar{t}}^2}{I^2}$$

A statistical procedure may now be used for testing variation in the two categories of boards (Hines and Montgomery, 1972).

To test whether the two means are equal, the first step is to test if the two variances are equal.

(a) Test that the two variances are equal, i.e., test the hypothesis $H_0 : \sigma_{t_1} = \sigma_{t_2}$ versus $H_a : \sigma_{t_1} \neq \sigma_{t_2}$

(subscript 1 refers to the category of boards currently being machine inserted, subscript 2 refers to boards currently being hand inserted but feasible to machine insert)

If $F_{data} \geq F_{1-\alpha/2,\ N_1-1,\ N_2-1}$

or $F_{data} \leq F_{\alpha/2,\ N_1-1,\ N_2-1}$

reject the hypothesis H_0; otherwise accept

where

$$F_{data} = \frac{S^2_{t_1}}{S^2_{t_2}}$$

and

$$F_{\alpha/2,N_1-1,N_2-1} = \frac{1}{F_{1-\alpha/2,N_1-1,N_2-1}}$$

Depending on the results of the above test, either of the following two tests can be used to test for means.

(b) Test that the two means are equal, i.e., $H_0 : \mu_{t_1} = \mu_{t_2}$

case-1 : $\sigma_{t_1} = \sigma_{t_2}$

If $t_{data} \geq t_{1-\alpha,N_1+N_2-2}$

reject H_0, otherwise accept

where

$$t_{data} = \frac{\bar{t}_1 - \bar{t}_2}{\sqrt{\frac{1}{N_1} + \frac{1}{N_2}} \sqrt{\left(\frac{1}{N_1+N_2-2}\right)\left(\Sigma\left(\bar{t}_{1j} - \bar{\bar{t}}_1\right)^2 + \Sigma\left(\bar{t}_{2j} - \bar{\bar{t}}_2\right)^2\right)}}$$

Case-2: $\sigma_{t_1} \neq \sigma_{t_2}$

If $t_{data} \geq t_{1-\alpha,\upsilon}$

reject H_0; otherwise accept

where

$$t_{data} = \frac{\bar{t}_1 - \bar{t}_2}{\sqrt{\frac{S^2_{\bar{t}_1}}{N_1} + \frac{S^2_{\bar{t}_2}}{N_2}}}$$

and

$$\upsilon = \left[\frac{\left(S^2_{\bar{t}_1}/N_1 + S^2_{\bar{t}_2}/N_2\right)^2}{\left(\frac{S^2_{\bar{t}_1}/N_1}{N_1 + 1}\right)^2 + \left(\frac{S^2_{\bar{t}_2}/N_2}{N_2 + 1}\right)^2}\right] - 2$$

Sequencer

Sequencers come in configurations which are integer multiples of a basic 20-station automated module with each station capable of handling one type of component or part number. The basic module can be expanded into 160 stations by adding 20-station modules. Since the sequencer is available in different configurations, the first step in evaluating the capital expenditure required for the sequencers is to find the optimum number and mix of sequencers required for each alternative.

An integer programming model is developed to determine the optimum number and size of sequencers required to meet production requirements for each alternative. Let

C_j = total cost per annum of sequencer with 20 x j heads

Y_j = minimum number of type-j sequencers required

X_{ij} = number of type-i boards required on type-j sequencer for a given time period

V_i = number of type-i boards required to meet the production requirement for a given time period

T_j = production time available for type-j sequencer in a given time period

t_{ij} = set up time per sequence for type-i board on type-j sequencer (a sequence is the output tape from the sequencer containing components for one board, arranged in an order for ease of insertion)

r_{ij} = run time per sequence for type-i board on type-j sequencer

n = number of sequencer sizes

Objective Function

$$\text{Minimize } Z = \sum_{j=1}^{n} C_j Y_j$$

Constraints

$$\sum_{i=1}^{n} (T_{ij} + Y_{ij}) X_{ij} \leq T_j Y_j \qquad \text{, for all } j$$

$$\sum_{j=1}^{n} X_{ij} \geq V_i \qquad \text{, for all } i$$

$$X_{ij} \geq 0 \qquad \text{, for all } i, j$$

$$Y_j \quad \text{integer}$$

The objective function minimizes the total sequencer cost. The first constraint states that for each type of sequencer, the total time required on the sequencer cannot exceed the total available production time during a given time period. According to the second constraint, the total number of boards of a particular type allocated to different sequencer sizes must satisfy the production requirements for that type of board. Since sequencers cannot be purchased as fractions, Y_j is constrained to be an integer; also, there cannot be negative allocation of boards to sequencers and X_{ij} is constrained to be non-negative.

The total cost, C_j, includes capital, operating, and maintenance costs. Capital cost per annum is the initial cost of the sequencer times the present worth discount factor, (P/F,i,n), taken over the life of the sequencer. The interest factor, i, used in the discount factor is the current minimum acceptable rate of return at TEK (30 percent). Operating cost represents the direct labor cost and the maintenance cost is estimated at five percent of the operating cost.

The board requirement, V_i, is evaluated based on current circuit board demand and a 15 percent annual growth rate. The production time available for a sequencer based on a one-year production period, T_i, is 3,500 hours (50weeks/year, five days/week, 14 hours/day).

The set up and run times for boards on different sizes of sequencers are evaluated based on current sequencing operations at TEK. The current sequencing operation uses 80-head sequencers. The run times and set up times for boards currently being sequenced are available as the standard times being used by the machine insertion area. A random sample of boards was chosen to develop regression equations for determining run time and set up time for boards with different part numbers, i.e., type of components, on an 80-head sequencer. In these regression equations, the run and set up times are expressed as a function of part numbers per board. The equations can be represented as

$$t = a_0 + a_1 p$$

$$r = b_0 + b_1 p$$

where t = average set up time per sequence on an 80-head sequencer

r = average run time per sequence on an 80-head sequencer

p = insertable part numbers per board

a_0, a_1, b_0, b_1 are known constants

As Table I shows, the boards have been dividied into various categories based on the number of insertable part numbers per board. The value of p to be used in the regression equations is the midpoint of the range for each board category.

TABLE I. RUN AND SET UP TIMES ON SEQUENCERS

	Mean Set Up Time (Heads on Sequencer)				Mean Run Time (Heads on Sequencer)			
Insertable part #/board	20	40	60	80	20	40	60	80
0-20	t_{11}	t_{12}	t_{13}	t_{14}	r_{11}	r_{12}	r_{13}	r_{14}
21-40	t_{21}	t_{22}	t_{23}	t_{24}	r_{21}	r_{22}	r_{23}	r_{24}
41-60	t_{31}	t_{32}	t_{33}	t_{34}	r_{31}	r_{32}	r_{33}	r_{34}
61-80	t_{41}	t_{42}	t_{43}	t_{44}	r_{41}	r_{42}	r_{43}	r_{44}

In the table above,

t_{ij} = set up time per sequence for type-i board on type-j sequencer

r_{ij} = run time per sequence for type-i board on type-j sequencer

The times for running boards on an 80-head sequencer obtained from the regression equations are then used to estimate run times and set up times for running boards on other types of sequencers, i.e., sequencers with different numbers of heads. The run time of a sequencer depends on the number of insertable components per sequence and is independent of the number of part numbers per sequence. For example, a board with 20 part numbers may have 50 insertable components; however, the time for sequencing 50 components will be the same whether a 20-head or an 80-head sequencer is used. Consequently, the run time for a specific board is independent of the type of sequencer used, or in terms of the notation used in Table I,

$$r_{11} = r_{12} = r_{13} = r_{14}$$

$$r_{21} = r_{22} = r_{23} = r_{24} \text{ , etc.}$$

The set up time is the time involved in changing the reels on a sequencer when changing from one run to another. Since the time to change a reel is constant, the set up time is proportional to the number of reel changes per set up. For a specific board, the set up time will be slightly less on a sequencer with more heads. As an example, the set up time for a board with 20 part numbers will be less on a 40-head sequencer than on a 20-head sequencer. This is because the 40-head sequencer will have a greater number of common reels which do not need to be changed between any two successive runs. However, since the data is only available for an 80-head sequencer, it is difficult to estimate the difference in set up times for a board on different sequencers. Therefore, the set up time is assumed to be constant for a board on all types of sequencers if the number of insertable part numbers is less than or equal to the number of heads on the sequencer.

$$t_{11} = t_{12} = t_{13} = t_{14}$$

$$t_{22} = t_{23} = t_{24}$$

$$t_{33} = t_{34}$$

The set up time for boards with insertable part numbers greater than the sequencer heads on which they are to be sequenced, is treated differently. Consider setting a run for a board with 40 insertable part numbers on a 20-head sequencer. To complete one sequence, part of the sequencing tape with the first set of 20 reels is generated; all of the 20 reels are then changed to the next set of 20 reels to complete the sequence. The reels are then changed back to the first set of 20 reels to start a new sequence. Thus, for a run of 50 sequences, 100 changes of 20 reels each will be required to complete the run. The alternate approach could be to run two separate sequences of 20 part numbers and then use two sequenced tapes on a component inserter. However, this will result in a substantial increase in set up time on the component inserter. In either case, the set up time is high enough to make the combinations economically infeasible. These combinations have, therefore, been neglected in this analysis, i.e.,

$$t_{21} = 0$$

$$t_{31} = t_{32} = 0$$

$$t_{41} = t_{42} = t_{43} = 0$$

In developing the sequencer requirement, only sequencers with up to 80 heads have been considered. This is because more than 99 percent of the total boards by volume produced at TEK have less than 80 part numbers per board. Table II shows the distribution of boards based on insertable part numbers per board.

TABLE II. DISTRIBUTION OF BOARDS AT TEK BASED ON INSERTABLE PART NUMBERS PER BOARD.

Insertable part #/board	Percent boards by volume
0-20	86.36
21-40	8.05
41-60	3.59
61-80	1.37
81-100	0.51
more than 100	0.12

The mixed integer programming model may now be solved using the branch and bound algorithm on MPOS (Multi-Purpose-Optimization System).

Direct Labor Cost

Direct labor cost includes the cost of labor required for operating the machines and for manual operations. The total labor cost may be evaluated as the product of the total number of employees required and the salary per annum for one employee. The salary includes both the base pay and the benefits. The benefits at TEK are estimated as 20 percent of the base pay.

The number of machine operators is dependent on the number of machines tended by one or more operators. This number is determined by the requirements of the job. In this analysis, it will be assumed that each machine is tended by one operator per shift which is consistent with current TEK practices.

In the case of manual assembly operations, the number of employees required is determined in the same way as the machine requirement.

$$A_j = \sum_{i=1}^{n} \frac{P_{ij}T_{ij}}{C_{ij}}$$

where, A_j = number of operators necessary for operation j

P_{ij} = desired production rate for product i on assembly j, pieces per production period

T_{ij} = standard time to perform operation j on product i, hours per piece

C_{ij} = time available for production, hours per period

n = number of products produced

The production rate is evaluated using the current production requirements and a 15 percent annual growth rate. The standard times for performing different operations are based on current MTM standards being used at TEK.

Inspection Cost

The nature of the electronics industry requires a very stringent quality check of finished circuit boards. To meet this high quality standard, a number of inspections are carried out. These range from simple manual inspections to the use of highly expensive in-circuit and functional testers. The investment in the inspection equipment is accounted for in the capital cost. The operating cost may be evaluated using the procedure described for labor cost, i.e., the testing machines are tended by one operator per machine per shift and for manual inspection, the operator requirement is based on the current MTM standards used at TEK.

Training Cost

There are two major components of training cost:

1. Administrative cost associated with hiring. Estimates obtained from the personnel department at TEK indicate that a cost of $500 is incurred every time a new employee is hired.

2. Learning curve factor. This accounts for the production lost during the training period. A learning curve model developed by Towill (1976) is used to evaluate the lost production.

Let

$Y_m(t)$ = output at time t

Y_c = output at time t=0

$Y_c + Y_f$ = output at time t=∞

τ = model time constant

The equation relating output to time, as given by Towill (1976), is $Y_m(t) = Y_c + Y_f\ (1 + e^{-t/\tau})$. This is shown graphically in Figure 4.

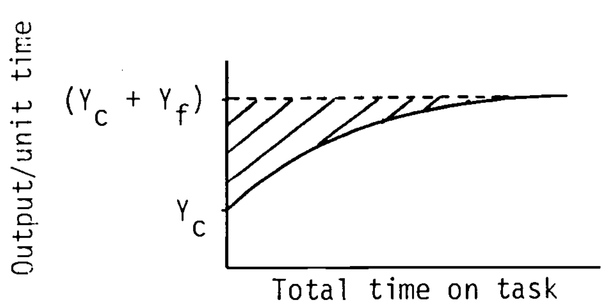


Figure 4. Learning curve (Towill, 1976)

This model is different from the standard learning curve model. The standard model can be represented as follows (Bump, 1974):

$$Y = aX^b$$

where, Y = the average number of hours per unit required to produce a total of X units.

a = the number of hours required to produce the first unit

X = the cumulative number of units to be produced

b = the index of learning

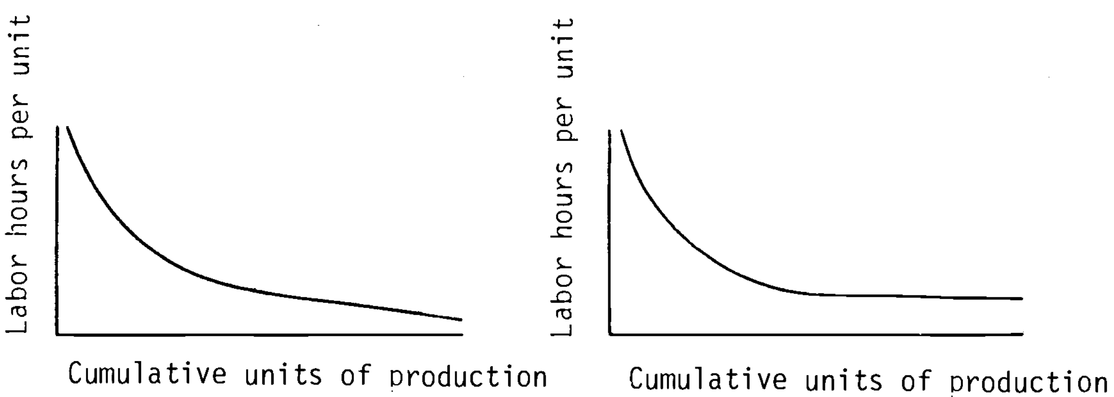
The index of learning, b, depends on the learning rate and may be defined as

$$b = \frac{\log(\text{learning rate})}{\log 2}$$

For an 80 percent learning rate

$$b = \log(0.8)/\log 2 = -0.3219$$

Since b is always a negative number, the average time required to produce X units decreases to zero as X becomes very large. This is portrayed graphically in Figure 5(a). However, in practice, the production of one unit requires some minimum amount of time. This is the steady state time which an experienced operator will take to produce a unit of product. The model used in this study takes this into account, as is shown in Figures 4 and 5(b).



(a) Standard Model $Y = aX^b$ (b) Model used here $Y_t = Y_c + Y_f(1+e^{-t/\tau})$

Figure 5. Comparison of learning models.

The parameters Y_c, Y_f, and τ are functions of task and many other variables. Towill (1976) gives values of these parameters for a number of different industries, based on a worldwide collection of industrial case studies. The values evaluated for electronic assembly operations are:

$$\frac{Y_c + Y_f}{Y_c} = 6.50$$

$$\tau(\text{weeks}) = 3$$

From the model equation, number of units produced to time T can be evaluated as

$$\int_0^T Y_m(t)dt = \int_0^T Y_c dt + \int_0^T Y_f(1 + e^{-t/\tau})dt$$

$$= (Y_c + Y_f)\,T - \tau Y_f(1 - e^{-T/\tau})$$

As T become large, the first term in the above expression represents steady-state production and the second term gives the production lost due to learning. The lost production is evaluated by taking the limit of the second term in the above expression as time becomes very large. The shaded area in Figure 4 represents lost production.

$$\text{Lost production} = \lim_{T\to\infty} \tau Y_f\,(1 - e^{-T/\tau})$$

$$= \tau Y_f$$

Let

$$Y_t = \text{total output at steady state } (T = \infty)$$

$$= Y_c + Y_f$$

Now

$$Y_c + Y_f = 6.5\ Y_c = Y_t$$

$$Y_t + 6.5\ Y_f = 6.5\ (Y_c + Y_f) = 6.5\ Y_t$$

$$Y_f = \frac{5.5}{6.5}\ Y_t$$

$$\text{Lost production} = \frac{5.5}{6.5}\ (3) = 2.54 \text{ weeks}$$

This implies that every time a new employee is hired, 2.54 week of production is lost. It is assumed that 2.54 weeks of lost production primarily represents the loss of the wages and benefits paid to the new employee during this training period. The training cost may then be evaluated as 2.54 weeks of pay and benefits for an employee times the number of new employees each year. The number of employees hired depends on the labor turnover rate. Since the actual turnover rate at TEK is supposed to be confidential, a 40 percent turnover rate is used in this analysis. This rate represents the people leaving this particular area, but not necessarily Tektronix.

Indirect Cost

The main component of indirect cost is the indirect labor cost which includes the cost of managerial and support staff. This cost element is substantially higher for the decentralized and satellite production arrangements because of the greater number of facilities to be supervised and maintained for the same amount of output. In evaluating the cost of managerial staff, a ratio of one manager to every 20 employees is used. This ratio was agreed upon after discussion with managers at TEK. Indirect labor cost includes both the base pay plus an additional 20 percent of the base pay as benefits.

Additional indirect cost will be incurred for maintaining the facilities. They include the cost of utilities and other facilities such as telephones, travel, and cafeterias. Since all business units at TEK are not yet decentralized, it is difficult to evaluate these factors for all the facilities. These costs have, therefore, been ignored for the present time.

Maintenance Cost

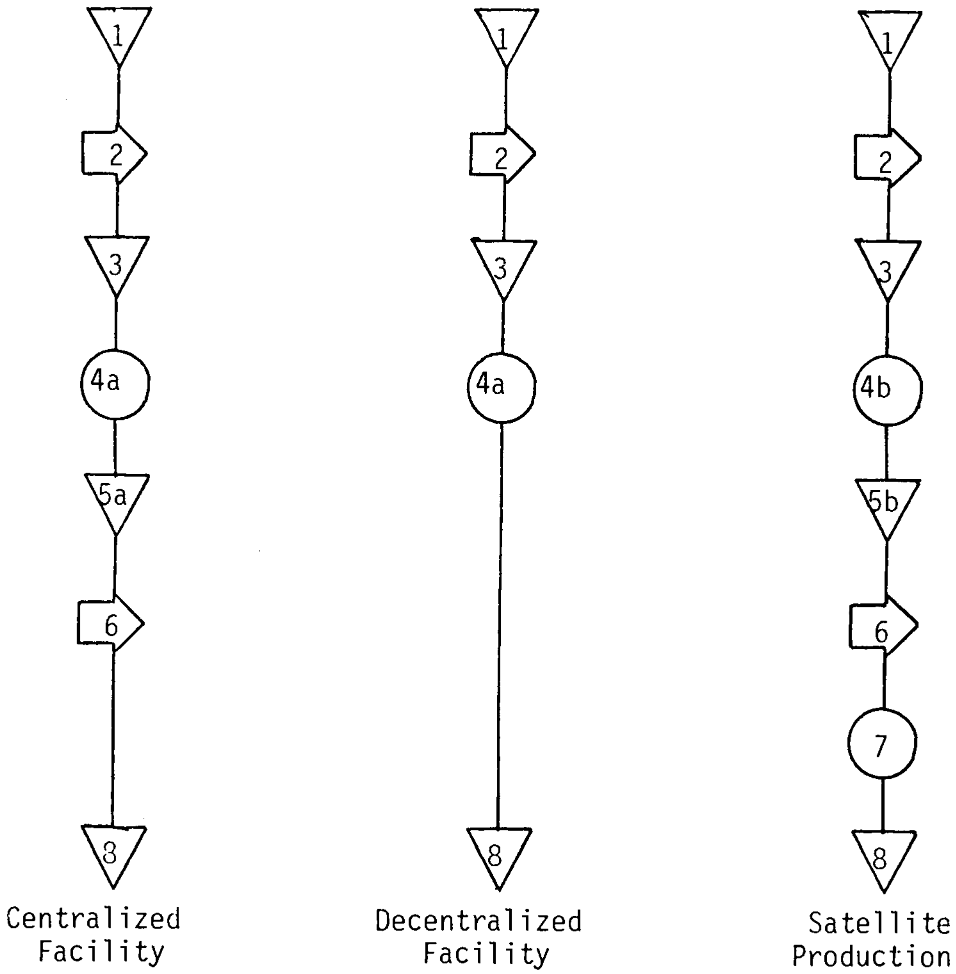
The difference in maintenance costs between two alternatives depends on the extra maintenance staff requirement and duplication of material required. For circuit board stuffing, the maintenance labor costs represent the major proportion of the total maintenance cost. This analysis assumes the difference in the fixed cost to be negligible as compared to the additional operating cost.

The maintenance operating expenses consist primarily of maintaining a pool of technicians and maintenance managerial staff. In evaluating the staff requirement, a ratio of one technician to four machines and one manager to every fifteen technicians is used. These figures represent the current TEK practice.

Distribution Cost

Distribution cost is directly proportional to the quantity of material being transported, the value of the material, and the time for which the material is in transit.

The flow process chart in Figure 6 shows the flow of material in centralized, decentralized, and satellite production facilities. In the central facility, circuit boards and components are moved from the warehouse to the production facility where they undergo component insertion and other manufacturing operations. The finished circuit



1. Warehouse storage
2. Transported to production facilities
3. Storage, waiting to be processed
4a. Circuit board manufacture
4b. Machine insertion
5a. Storage of finished boards
5b. Storage of semi-finished boards
6. Distribution to business units
7. Hand-insertion, flow soldering, and inspection
8. Storage, ready for use

Figure 6. Material flow through centralized, decentralized, and satellite facilities.

boards are then distributed to the business units for final utilization.

In the decentralized facility, the board are shipped directly to the business units where they are processed. No distribution cost is incurred since the boards are produced at the location where they are consumed.

For the satellite production arrangement, there is the initial movement of boards to a centralized machine insertion area where sequencing and insertion takes place. The boards are then distributed to the business units where remaining operations are performed.

The distribution cost of raw circuit boards is assumed to be the same for the three alternatives; particularly if the current practice of locating the warehouse next to the production facility is followed. Distribution cost is incurred for transporting finished boards in a centralized facility and semi-finished boards for satellite production.

The distribution cost may be estimated from the expression

Distribution cost = (Number of boards x Cost of insertion per board x Delivery time) x (Interest on tied-up capital)

The average delivery time at TEK is one day and the interest factor being used is 30 percent per annum. The cost of insertion represents the total dollars that have been invested in a board up to the time of distribution. For the centralized facility, the cost of insertion will be the total production cost since finished cirucuit boards are distributed. For satellite production, the boards are distributed after machine insertion and, hence, the cost of production associated with machine insertion alone constitutes the cost of insertion.

Cash Flow Analysis

After evaluating the different cost factors for the three alternatives, the next step in the analysis is to conduct a cash flow analysis so as to reduce the costs associated with each of the alternatives to a common economic measure for comparison purposes. The economic measure used in this analysis is the annual worth comparison.

The following assumptions have been made in carrying out the cash flow analysis:

1. Each piece of equipment is to be utilized for its full economic life.

2. Corporate cash flows are always going to be such that any tax savings may be realized.

3. Machines are not to be used after economic life.

4. All salvage values are assumed to be zero.

5. A 50 percent tax rate is used in this analysis.

6. Depreciation charges are accounted for using straight-line depreciation. Straight-line depreciation is currently being used at TEK in its economic evaluations and is used here to be consistent with TEK's practices.

In the annual worth comparison, all receipts and disbursements occurring over a study period are converted to an equivalent yearly uniform income or outlay to provide one comparison figure.

The annual worth comparison is based on the after tax cash flow. Table headings for the approach used to evaluate after tax cash flow are summarized below (Riggs, 1977).

End of Year (1)	Before Tax Cash Flow (2)	Depreciation Charges (3)	Taxable Income (2-3=4)	Taxes (4x tax rate=5)	After Tax Cash Flow (2-5)

Sensitivity Analysis

The analysis in this study uses an annual growth rate of 15 percent. A sensitivity analysis examines the effect of a change in production growth rate that may reverse the decision among alternatives.

The capacity and economic evaluation are carried out using annual growth rates of 10 and 20 percent. The procedure used in these evaluations is identical to the one used for the 15 percent annual growth rate--equipment and manpower evaluation for each alternative; conversion of these requirements to dollar values; and comparison of the annual equivalent cost for the three alternatives. The comparison of the annual worths may or may not show a reversal in the decision among alternatives.

IV. ANALYSIS OF RESULTS

The three alternatives for circuit board manufacture being compared in this study are centralized, decentralized, and satellite production. The comparison procedure involves the development of equipment and manpower requirements, conversion of these requirements into monetary units, and bringing the dollar values to a common base for comparison purposes according to the scheme developed in Chapter III.

The analysis in this study are conducted using an annual growth rate of 15 percent. An effort was made to develop a forecasting model to predict the future in circuit board demand. However, this model could not be developed due to the unavailability of past production records at TEK. The 15 percent annual growth rate has been predicted by the marketing group at TEK and is currently being used in the capacity and economic evaluations at TEK.

Tables III and IV show TEK's total circuit board and insertable circuit board requirements for the next five years. The figures have been developed based on current production requirements and a 15 percent growth rate per annum.

TABLE III. TEK'S TOTAL BOARD REQUIREMENT

Mode of Operation	Total Board Requirement Per Year				
	1981	1982	1983	1984	1985
Centralized	2,746,908	3,160,139	3,633,085	4,177,685	4,801,118
Decentralized					
IDD	445,146	512,111	588,573	677,008	778,037
COM	394,000	453,272	521,108	599,223	688,644
SID	823,349	947,210	1,088,969	1,252,207	1,439,072
LID	1,084,413	1,247,547	1,434,254	1,649,251	1,895,366

TABLE IV. TEK'S INSERTABLE BOARD REQUIREMENT

Mode of Operation	Insertable Board Requirement Per Year 1981	1982	1983	1984	1985
Centralized	2,383,665	2,742,251	3,152,656	3,625,243	4,166,232
Decentralized					
IDD	424,724	488,617	561,743	645,949	742,343
COM	276,162	317,707	365,255	420,007	482,683
SID	751,936	865,053	994,517	1,114,360	1,314,253
LID	930,843	1,070,875	1,231,142	1,415,691	1,626,952

The preceding figures are used in the development of capital and operating costs. In estimating the capital cost, the equivalent annual capital cost for each type of equipment is calculated separately. The equivalent annual cost includes the first cost of equipment converted to annual cost using the appropriate capital-recovery factor and the annual operating costs. The total capital cost per annum is obtained by summing up the equivalent annual capital cost for each type of equipment. The annual operating expenses are evaluated according to the model developed in Chapter III.

Sequencer

The first step in developing the sequencer cost estimate is to determine the optimum sequencer mix for each alternative. In order to apply the 0-1 integer programming model developed in Chapter III, estimates of the set up and run times must be developed for each part category. This is achieved using a random sample of 50 boards currently undergoing component insertion. The two regression equations for determining set up and run times on an 80-head sequencer were obtained using SIPS (Statistical Interactive Programming System).

The least squares equation relating set up time to insertable part number per board is

$$T = 0.675 + 0.0135\ P$$

where T is the set up time per run on an 80-head sequencer and P is the insertable part numbers per board. Both the slope and intercept were statistically significant with t-values of 2.903 and 7.953, respectively, for 48 degrees of freedom.

The set up time obtained from the regression equation above gives the set up time per run. The set up time per sequence is obtained by dividing the set up time per run by the average number of boards per run. The average number of boards per run for different part categories has been estimated from the current sequencing operation at TEK and are listed in Table V.

TABLE V. AVERAGE BOARDS PER RUN FOR DIFFERENT PART CATEGORIES

Part Category (Insertable part numbers/board)	Average Number of Boards Per run
0-20	250
21-40	78
41-60	70
61-80	70

The run time per sequence for an 80-head sequencer, R, is related to the insertable part numbers per board, P, by the relation

$$R = 0.0659912 + 0.0012539\ P$$

The slope and intercept for this regression equation were statistically significant with t-values of 2.733 and 7.966, respectively, for 48 degrees of freedom. Examination of the plot of residuals against the independent variable for both the regression equations did not suggest any lack of fit for the linear models.

The run and set up times for boards on an 80-head sequencer are obtained from the two regression equations by substituting the values for part number per board, P. The value of P to be used in solving the regression equations is the midpoint of the range for each board category.

The run and set up times obtained for an 80-head sequencer are then used to develop times for other sequencers. The run time on a sequencer depends on the number of insertable components per sequence and is independent of the number of part numbers per sequence. For example, a board with 20 part numbers may have 50 insertable components; however, the time for sequencing 50 components will be the same whether a 20-head or an 80-head sequencer is used. Therefore, the run times for a particular board category, developed for the 80-head sequencer, may also be used for other types of sequencer.

The set up time for boards is proportional to the number of reel changes on the sequencer per set up. For boards with insertable part numbers greater than the sequencer heads on which they are to be sequenced, the set up time is too high to make the run economically feasible. Consider setting a run for a board with 40 part numbers on a 20-head sequencer. To complete one sequence, part of the sequencing tape with the first set of 20 reels is generated; all the 20 reels are then changed to the next set of 20 reels to complete the sequence. The reels are then changed back to the first set of 20 reels to start a new sequence. For a run of 50 sequences, 100 changes of 20 reels each will be required to complete the run. This will result in high set up time. Therefore, all such combinations have been neglected in this analysis.

The set up time for a board category with insertable part numbers less than the heads on the sequencer on which they are to be processed is the same on all types of sequencers. In practice, the set up time for a specific board will be slightly less on a sequencer with more heads because fewer reels will have to be changed from one run to another. However, since data is only available for an 80-head sequencer, it is difficult to estimate this difference. The set up times for different categories obtained for an 80-head sequencer are, therefore, assumed to be constant for each part category on all types of sequencers.

The run and set up times estimated in this manner for different board categories are shown in Table VI.

TABLE VI. SET UP AND RUN TIMES ON SEQUENCERS

Part Category (insertable part numbers/board)	Mean Set Up Time/Sequence (hrs) (sequencer heads)				Mean Run Time/Sequence (hrs) (sequencer heads)			
	20	40	60	80	20	40	60	80
0-20	.003244	.003244	.003244	.003244	.00785	.00785	.00785	.00785
21-40	-	.013896	.013896	.013896	-	.01035	.01035	.01035
41-60	-	-	.019381	.019381	-	-	.01285	.01285
61-80	-	-	-	.023278	-	-	-	.01535

The time values in Table VI are used in the mixed integer program to determine the optimum mix of sequencers for the centralized and each of the decentralized facilities. The integer programming model determines the mix of sequencers which will minimize the total cost of sequencing subject to production requirement and production time constraints. The sequencers required to meet the 1985 production requirements are shown in Table VII. The results of the MPOS runs for each year are included in Appendix B.

TABLE VII. TEK'S SEQUENCER REQUIREMENTS FOR 1985

Mode of Operation	Sequencers Required (sequencer head) 20	40	60	80	Total Cost $/yr.
Centralized	12	2	2	1	350,701.41
Decentralized	12	2	0	4	390,585.72
IDD	2	0	0	1	
COM	1	0	0	1	
SID	4	1	0	1	
LID	5	1	0	1	
Capital cost per sequencer ($)	42,000	57,750	73,500	89,250	
Operating cost per sequencer ($/yr)	13,728	13,728	13,728	13,728	
Equivalent annual cost/sequencer ($/yr)	18,349.32	22,656.32	26,963.31	31,270.31	

Since satellite production has a centralized machine insertion area, its sequencer requirements are the same as the centralized facility.

Table VIII summarizes the sequencer requirements for centralized and decentralized production alternatives over the next five years. Even though the sequencer requirements are the same for centralized

TABLE VIII. SEQUENCER REQUIREMENTS

Mode of Operation	Sequencer Requirements 1981	1982	1983	1984	1985
Centralized	11	13	15	17	17
Decentralized	11	13	16	17	18

and decentralized production for some years, the sequencer mix for the two alternatives is different. The difference in sequencer mix results primarily from having at least one 80-head sequencer at each production facility. The 80-head sequencer is required to sequence the small proportion of boards with more than 20 insertable part numbers per board. One such sequencer is required for each of the decentralized facilities; this results in a higher sequencing cost for the decentralized alternative.

The procedure for translating sequencer requirements into dollar values involves the determination of total annual cost (first cost plus the operating expenses) for one sequencer, which is then multiplied by the total number of sequencers to obtain the total annual cost. The procedure is illustrated for a 20-head sequencer.

The centralized facility requires twelve 20-head sequencers in 1985 to meet the production requirements. The first cost for a 20-head sequencer is $42,000 and the annual operating cost, which accounts for both the operator's pay and benefits, is $13, 728. The after tax cash flows for one 20-head sequencer are calculated as follows:

Year	Before Tax Cash Flow (BTCF)	Depreciation	Taxable Income	Tax Benefits (50% tax rate)	After Tax Cash Flow (ATCF)
0	-42,000				-42,000
1-10	-13,728	-4,200	-17,928	8,964	- 4,764

$$\text{Annual cost} = AC = -42{,}000\ (A/P,i,n) - 4{,}764$$
$$= -42{,}000\ (A/P,30,10) - 4{,}764$$
$$= -18{,}349.32$$

In 1985, twelve 20-head sequencers are required. The total cost of the sequencers is then obtained as

$$12 \times 18{,}349.32 = \$220{,}191.84$$

The equivalent annual cost may be obtained for each of the different sequencer types similarly. These costs are shown as the last row in Table VII. The total annual sequencing costs are then obtained by summing up the annual costs for all types of sequencers for that year. For example, the total sequencing cost for centralized production may be obtained as

$$12 \times 18{,}349.32 + 2 \times 22{,}656.32 + 2 \times 26{,}963.31 + 1 \times 31{,}270.31$$
$$= \$350{,}701.41$$

The annual sequencing costs for centralized and decentralized production facilites over the five-year study period are summarized in Table IX.

TABLE IX. ANNUAL SEQUENCING COSTS

Mode of Operation	Annual Sequencing Cost ($) 1981	1982	1983	1984	1985
Centralized	240,605.49	272,997.12	314,002.76	359,315.40	350,701.41
Decentralized	292,289.44	303,146.11	353,887.08	380,850.39	390,585.72

Component Inserter

The first step in developing cost estimates for component inserters is to determine the number of component inserters required to meet the production requirements. This requires the computation of insertion times for the insertion operations. A statistical procedure was developed in Chapter III to calculate the mean insertion times for currently insertable and potentially insertable boards separately, which are then tested to see if there is any significant variation between the two insertion times. The mean insertion time for each category of board is estimated by taking ten random samples of five boards each and calculating the mean insertion time for each sample. The overall mean insertion time for the process is then calculated as the average of the insertion times for each sample.

An overall mean insertion time of 0.0161 hours per board an a population variance estimate of 0.00011142 was obtained for boards that are currently machine inserted. This results in an estimated variance for the population mean of 0.00001114 (population variance/sample size, N). For potentially insertable boards, the mean insertion time was 0.02051 hours per board and the population variance estimate was 0.00019127; the estimated variance of the population mean is then 0.0000191.

The distribution of the production times appears to be skewed. However, by using the average insertion time as the estimator of the production time and by using the means from small samples, the distribution of means is approximated by the normal distribution. The F-test and t-tests may mow be used for testing the equality of two means.

The first step in testing the equality of two means is to test if the two variances are equal. An F-value of 1.72 failed to reject the hypothesis that the two variances are equal at a significance level of 0.05. The subsequent t-test yielded a value of 0.8034. The critical t-value at a significance level of 0.05, obtained from t-distribution tables, is 1.734. Therefore, the hypothesis that the two means are equal can be accepted. Since the calcuated F-and t-values are not even close to the significant values, the non-normality would not have any effect on the final result. An aggregate sample then yielded a mean insertion time per board of 0.0183 hours for the insertion process

Given the mean insertion time per board, the number of component inserters required to meet production may now be calculated. For example, the insertable board requirement for the centralized facility in 1985 is projected to be 4,166,232 boards. There are 3,500 production hours available per annum, based on 50 week per year, five days per week, and 14 hours per day. The current maintenance records at TEK show the utilization of component inserters to be 89.79 percent. The component inserters required to meet 1985 production are then calculated as

$$\text{Component inserters required to meet 1985 production} = \frac{4{,}166{,}232 \times 0.0183}{3{,}500 \times 0.8979}$$

$$= 25$$

Table X shows the component inserter requirements for centralized and decentralized facilities over the next five years. The requirements for satellite production are the same as that for the centralized facility since satellite production has a centralized machine insertion area.

TABLE X. COMPONENT INSERTER REQUIREMENTS

Mode of Operation	Component Inserter Requirements 1981	1982	1983	1984	1985
Centralized	14	16	19	22	25
Decentralized	16	18	21	25	28

The procedure used for developing cost estimates is similar to the one used for sequencers, i.e., calculating the equivalent annual cost for one component inserter; the product of this equivalent annual cost with the number of component inserters required gives the total annual cost. The first cost of a component inserter is $68,250 and the annual operating cost is $12,708. The after tax cash flows are calculated as follows:

Year	Before Tax Cash Flow (BTCF)	Depreciation	Taxable Income	Tax Benefits (50% tax rate)	After Tax Cash Flow (ATCF)
0	-68,250				-68,250.00
1-10	-12,708	-6,825	-19,533	9,766.50	- 2,941.50

Annual cost = AC = -68,250(A/P,30,10) - 2,941.50

= -$25,017.65

In 1985, 25 component inserters are required for centralized production. The total annual cost is then 25 x 25,017.65 = $350,247.10. The total cost for other years is similarly obtained. Table XI shows the annual component insertion costs for centralized and decentralized facilities over the five-year period.

TABLE XI. ANNUAL COMPONENT INSERTION COSTS

Mode of Operation	Annual Component Insertion Cost ($) 1981	1982	1983	1984	1985
Centralized	350,247.10	400,282.40	475,335.35	550,388.30	625,441.25
Decentralized	400,282.40	450,317.70	525,370.65	575,405.95	650,458.90

Other Equipment

The procedure for developing cost estimates for hardware inserters, flow soldering machines, and the testing equipment is similar to that of component inserters. The initial step is to determine the production time per board and the machine utilization. A sampling procedure is used to facilitate the computations involved in estimating the production time. A random sample of 50 boards is used to determine the weighted average production time for the operations. Machine utilization is evaluated from the current maintenance records at TEK. The production times and machine utilization for each of the operations and the percentage of boards by volume that undergo these operations are summarized in Table XII.

TABLE XII. PRODUCTION TIMES, MACHINE UTILIZATIONS, AND EQUIVALENT ANNUAL COSTS FOR HARDWARE INSERTERS, FLOW SOLDERING MACHINES, AND TESTING EQUIPMENT.

Operation	Insertion or Testing Time (hrs/board)	Machine Utilization (%)	Percentage of Boards by Volume Undergoing Operation	Equivalent Annual Cost Per Machine ($/yr)
Hardware Insertion	0.0182	90	95	19,804.65
Flow Soldering	0.0196	85	74.52	35,067.30
Exploded Testing	0.25	95	100	11,511.90
In-circuit Testing	0.0286	90	70	40,536.50
Functional Testing	0.0769	90	21	88,392.00

The machines needed to meet the production requirements may now be calculated. For example, the 1985 projected forecast for the centralized facility is 4,801,118 boards. There are 3,500 production hours available per annum, and the mean insertion time per board and the machine utilization from Table XI are 0.0182 hours and 90 percent, respectively. The number of hardware inserters required for centralized production in 1985 is

$$\frac{4,801,118 \times 0.95 \times 0.0182}{3,500 \times 0.90} = 27$$

The number of hardware inserters, flow soldering machines, and testing equipment required to meet production in each of the next five years for the three alternatives are shown in Appendix B.

The cost estimating procedure is the same as used for sequencers and component inserters. It involves the development of equivalent annual cost per unit of equipment. These are shown in Table XII. The annual cost per unit is then multiplied with the number of units required to obtain the total annual cost.

The total annual machine cost for an alternative for any year may be obtained by summing the annual costs incurred for all types of equipment in that year. The total annual machine cost for the three alternatives over the next five years is summarized in Table XIII.

TABLE XIII. TOTAL ANNUAL MACHINE COSTS.

Mode of Operation	Total Annual Machine Cost (million $) 1981	1982	1983	1984	1985
Centralized	6.52	7.48	8.57	9.82	11.20
Decentralized	6.88	8.00	8.89	10.11	11.58
Satellite	6.75	7.86	8.78	10.03	11.50

The annual machine cost is highest for the decentralized facility since this arrangement splits up production into a number of small production cells. This results in lower machine utilization and consequently higher capital investment. The annual machine cost for satellite production in any year is lower than centralized production but higher than decentralized production. This is because the satellite arrangement has a centralized machine insertion area, but all other operations, including flow soldering and automatic testing, are decentralized.

Manual Operations

The cost associated with manual operations is the direct labor cost. The first step in evaluating the direct labor cost is to determine the manpower requirements for different manual operations. The estimation of manpower required to meet the production requirement is based on current MTM standards used at TEK. These standards have been developed by the time and standards group at TEK and are shown in Table XIV for the various manual operations.

TABLE XIV. PRODUCTION TIMES FOR MANUAL OPERATIONS.

Operation	Production Time Per Board (hrs)	Percentage of Boards by Volume Undergoing Operation
Hand insertion	0.2812	74.52
Hand adds, finishing	0.3879	98.01
Lead clipping	0.0153	60.34
Transistorising	0.1804	65.26
Inspection	0.0996	98.01

The manpower requirement may now be developed using MTM standards. As an example, the projected forecast for 1985 is 4,801,118 boards; of the total boards, 74.52 percent undergo hand insertion. The insertion time per board is 0.2812 hours and 3,500 hours are available in a production period. The number of operators required to meet 1985 hand insertion requirements may be calculated as

$$\frac{4,801,118 \times 0.7452 \times 0.2812}{3,500} = 288$$

The operator requirement for other operations may be calculated similarly. The number of operators required for hand operations (including hand insertion, hand adds, transistorising, clipping, inspection, and kit prep) for the three alternatives are shown in Table XV.

TABLE XV. OPERATOR REQUIREMENTS FOR THE THREE ALTERNATIVES.

Mode of Operation	Operator Requirements 1981	1982	1983	1984	1985
Centralized	899	1,035	1,188	1,366	1,563
Decentralized	906	1,042	1,194	1,373	1,578
Satellite	974	1,120	1,284	1,477	1,697

The higher operator requirement for the satellite arrangement is due to the additional inspection of machine-inserted boards before they are distributed to the various business units. This inspection is not required for the centralized and decentralized alternatives since all operations are performed at the same location.

The manpower requirement may now be used to develop annual operating costs. The operating costs consist of the wages and benefits paid to the workers. Since these expenses primarily represent costs, they are subject to taxes and are available for tax benefits. At a 50 percent tax rate, the tax benefits are half the before tax cash flow (BTCF), therefore, the after tax cash flow (ATCF), which is the BTCF minus the tax benefits, is half of the BTCF. For example, if the annual renumeration for an employee is $12,708, the after tax cash flow will be $6,354. Since this amount represents annual cost, the total annual operating expenses may be obtained by multiplying the ATCF by the number of operators per year. The operating costs for the three alternatives over the five-year period are shown in Table XVI. The annual operating costs include inspection costs.

TABLE XVI. ANNUAL OPERATING COSTS FOR THE THREE ALTERNATIVES.

Mode of Operation	Annual Operating Costs (million $) 1981	1982	1983	1984	1985
Centralized	5.59	6.44	7.39	8.50	9.75
Decentralized	5.64	6.48	7.43	8.54	9.82
Satellite	6.09	6.98	8.00	9.20	10.57

Other Annual Costs

Besides direct labor and inspection, other sources of annual expenditure are training costs, managerial costs, maintenance costs, and distribution costs. Training costs incude the administrative cost associated with hiring and the cost of lost production during the training period. The administrative cost of hiring is estimated by the personnel department at TEK to be $500 per new employee hired. The learning curve model presented in Chapter III showed that every time a new employee is hired, 2.54 weeks of production is lost as a result of training. The 2.54 weeks of lost production primarily represents the loss of wages and benefits paid to the employee during this period. For an employee whose annual pay is $12,708, 2.54 weeks of employment will cost (2.54 x 12,708)/50 = $645.57. The annual cost of hiring and training before taxes will then be 500 + 645.57 = $1,145.67. At a 50 percent tax rate, the after tax cash flow is half this amount, or $572.78. The total number of workers (machine plus manual operators) employed for centralized production in 1985 is projected to be 2,115. At a 40 percent labor turnover rate, the number of new employees hired during the year will be 846. The total training cost for 1985 centralized production may then be calculated as 846 x 572.78 = $278,372.

The annual managerial expense depends on the number of managers required to supervise production operations per year. The managerial requirement is determined by using a ratio of one manager to every 20 operators. This ratio is used to be consistent with the current TEK practice. Based on a requirement of supervising 2,115 operators, of which 547 are machine operators for the centralized facility in 1985, a total of 107 managers will be required. The annual pay for a manager is $25,404, which results in a before tax annual cost of $2,718,228 (107 x 25,404). The after tax annual cost is half of this amount, or $1,359,114.

The maintenance operating expenses consist primarily of maintaining a pool of technicians and maintenance managerial staff. To be consistent with TEK's current practice, a ratio of one technician to every four machines and of one manager for every fifteen technicians is used to develop the maintenance staff requirements. There will be 165 sequencers, component inserters, hardware inserters, flow soldering machines, and in-circuit and functional testers to be maintained for a centralized facility in 1985. Based on the above ratios, this will require 42 technicians and three maintenance managers. The annual pay for a technician is $17,292 and for a manager, $20,160. The before tax annual maintenance cost for a centralized facility in 1985 can then be calculated as

$$17{,}292 \times 42 + 20{,}160 \times 3 = \$786{,}744.$$

The after tax maintenance cost is then $393,372.

The distribution cost is incurred in distributing finished circuit boards for a centralized facility and semi-finished, i.e., machine inserted boards for satellite production. The distribution cost may be evaluated from the following expression.

Distribution cost = (Number of boards x Cost of insertion per board

x Delivery time) x (Interest on tied up capital)

The average delivery time based on current distribution procedure at TEK is one day, and the interest factor is 30 percent per annum (or 0.12 percent per day). The cost of insertion represents the total dollars that have been invested in a board up to the time of distribution. For the centralized facility, the cost of insertion will be the total production cost, since finished circuit boards are distributed. For satellite production, the boards are distributed after machine insertion and, hence, the cost associated with machine insertion and the subsequent inspection alone constitute the cost of insertion. The total production cost for a centralized facility in 1985 has been estimated as 20.95 million dollars. The distribution cost may then be calculated as

$$20.95 \times 0.0012 \times 1 = \$0.025 \text{ million.}$$

For the same year, the machine insertion and inspection costs for satellite production are estimated as 2.27 million dollars. The distribution cost is then $2.27 \times 0.0012 \times 1 = \$2,720$.

The procedures described above have been used to develop cost estimates for the three alternatives. A summary cost sheet for each of the three alternatives is shown in Tables XVII through XIX.

TABLE XVII. ANNUAL COSTS FOR CENTRALIZED FACILITY

Costs	Annual Costs (million $) for Centralized Facility 1981	1982	1983	1984	1985
Machine	6.52	7.48	8.57	9.82	11.20
Direct Labor	5.10	5.87	6.74	7.75	8.90
Inspection	0.49	0.57	0.65	0.74	0.85
Training	0.28	0.32	0.37	0.42	0.48
Indirect	0.78	0.90	1.03	1.18	1.36
Maintenance	0.24	0.26	0.30	0.35	0.39
Distribution	0.015	0.017	0.019	0.022	0.025
TOTAL	13.425	15.417	17.679	20.282	23.205

TABLE XVIII. ANNUAL COSTS FOR DECENTRALIZED FACILITY

Costs	Annual Costs (million $) for Decentralized Facility 1981	1982	1983	1984	1985
Machine	6.87	8.00	8.89	10.11	11.58
Direct Labor	5.14	5.91	6.77	7.80	8.95
Inspection	0.50	0.57	0.65	0.74	0.86
Training	0.28	0.33	0.37	0.43	0.49
Indirect	0.83	0.94	1.07	1.22	1.39
Maintenance	0.27	0.31	0.33	0.38	0.42
Distribution	(No distribution cost is incurred since boards are consumed at the production facility)				
TOTAL	13.89	16.06	18.08	20.68	23.69

TABLE XIX. ANNUAL COSTS FOR SATELLITE PRODUCTION

Costs	Annual Costs (million $) for Satellite Production 1981	1982	1983	1984	1985
Machine	6.75	7.86	8.78	10.03	11.50
Direct Labor	5.14	5.91	6.77	7.80	8.95
Inspection	0.92	1.07	1.23	1.40	1.62
Training	0.30	0.34	0.39	0.45	0.52
Indirect	0.83	0.97	1.09	1.25	1.44
Maintenance	0.25	0.28	0.32	0.36	0.41
Distribution	0.0016	0.0018	0.0021	0.0024	0.0027
TOTAL	14.192	16.432	18.582	21.292	24.443

The total annual costs for the three alternatives are plotted in Figure 7.

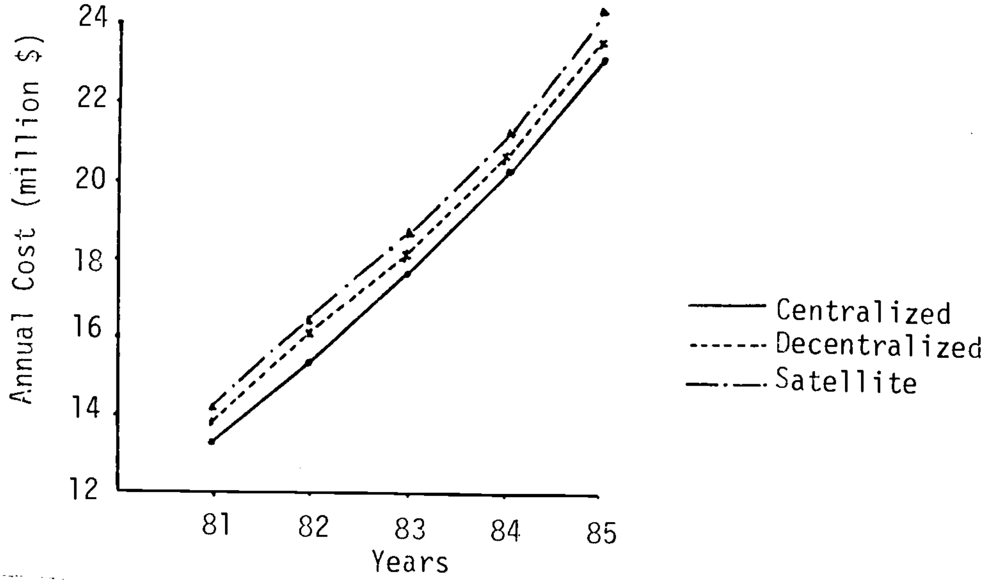


Figure 7. Annual costs for the three alternatives (15% growth rate).

Cash Flow Analysis

The cost values obtained in the previous sections are reduced to an annual cost figure for comparison purposes.

Centralized production. The annual costs for the centralized facility are shown in the form of a cash flow diagram in Figure 8 (all cost figures are in millions of dollars).

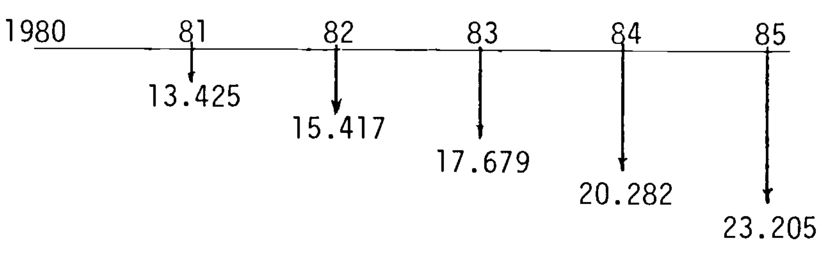


Figure 8. Cash flow diagram for centralized production

The present worth for these costs may be calculated as follows:

$$PW = 13.425(P/F,30,1) + 15.417(P/F,30,2) + 17.679(P/F,30,3) + 20.282(P/F,30,4) + 23.205(P/F,30,5)$$

$$PW = 13.425x0.76923+15.417x0.59172+17.679x0.45517+20.282x0.35013$$
$$+23.205x0.26933$$
$$= 40.848$$

The annual worth can be determined using the present worth as

$$AW = PW(a/p,30,5)$$
$$= 40.848 \times 0.41058$$
$$= 16.771$$

<u>Decentralized production</u>. The cash flow diagram for decentralized production is shown in Figure 9.

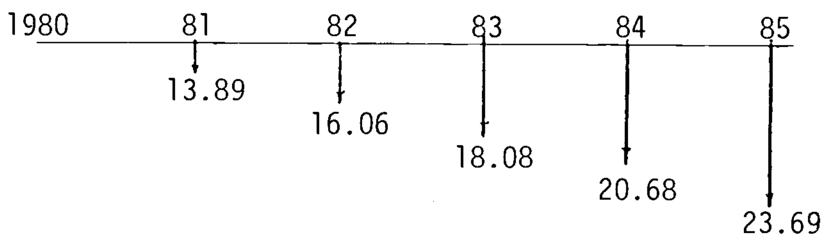


Figure 9. Cash flow diagram for decentralized production

The present worth is calculated as follows:

$$PW = 13.89(P/F,30,1)+16.06(P/F,30,2)+18.08(P/F,30,3)+20.68(P/F,30,4)$$
$$+23.69(P/F,30,5)$$
$$= 42.04$$

The annual worth for this alternative is then equal to

$$AW = 42.04(a/p,30,5)$$
$$= 17.261$$

<u>Satellite production</u>. The cash flow diagram for satellite production is shown in Figure 10 on the following page.

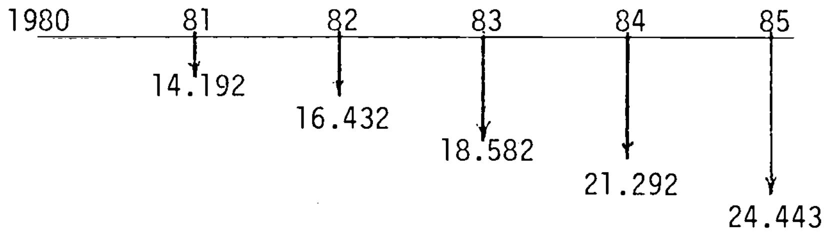


Figure 10. Cash flow diagram for satellite production

$$PW = 14.192(P/F,30,1)+16.432(P/F,30,2)+18.582(P/F,30,3)$$
$$+21.292(P/F,30,4)+24.443(P/F,30,5)$$
$$= 43.14$$
$$AW = 43.14(a/p,30,5)$$
$$= 17.712$$

A comparison of the annual worth for the three alternatives shows that the annual cost for the centralized facility is the lowest. This was to be expected since centralized production requires the least amount of capital outlay and, except for distribution costs, has lower annual costs than either of the other two alternatives. Satellite production results in maximum annual cost, primarily due to the high cost of inspection of semi-finished boards.

Effects of Varying Annual Growth Rate

The capacity and economic evaluations were carried out using a growth rate of 15 percent per annum. In any economic situation, it is difficult to predict precisely the course of future events due to the enormity of the factors involved. The predicted economic growth rate is one factor which may be subject to unforeseen variations.

To observe the effect of change of growth rate on the final outcome of the analysis, the alternatives were re-examined using annual growth rates of 10 percent and 20 percent. The procedure used in the analysis for each of the two growth rates is the same as for a 15 percent growth rate per annum. It involves the development of equipment and manpower required to meet the production requirements, conversion of these requirements into dollar values, and reduction of these costs to an annual worth basis for comparison purposes. The circuit board requirements and development of cost estimates at 10 and 20 percent growth rates are shown in Appendices C and D. However, Tables XX and XXI show the total annual costs for the three alternatives over a five-year period at 10 and 20 percent growth rates. These costs are then plotted in Figures 11 and 12.

TABLE XX. ANNUAL COSTS FOR THE THREE ALTERNATIVES (10 PERCENT ANNUAL GROWTH RATE)

Mode of Operation	Annual Costs (million $) at 10% Annual Growth Rate 1981	1982	1983	1984	1985
Centralized	12.81	14.10	15.54	17.04	18.61
Decentralized	13.31	14.58	16.04	17.46	19.25
Satellite	13.59	14.94	16.49	17.93	19.71

TABLE XXI. ANNUAL COSTS FOR THE THREE ALTERNATIVES (20 PERCENT ANNUAL GROWTH RATE)

Mode of Operation	Annual Costs (million $) at 20% Annual Growth Rate 1981	1982	1983	1984	1985
Centralized	14.03	16.68	20.08	24.12	28.78
Decentralized	14.49	17.27	20.50	24.47	29.15
Satellite	14.84	17.72	21.05	25.28	30.05

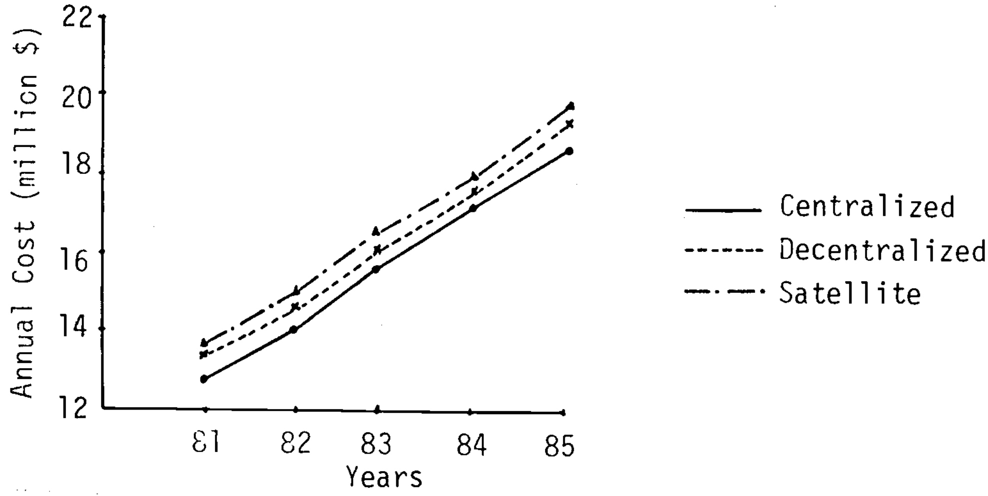


Figure 11. Annual cost for the three alternatives (10 percent annual growth rate).

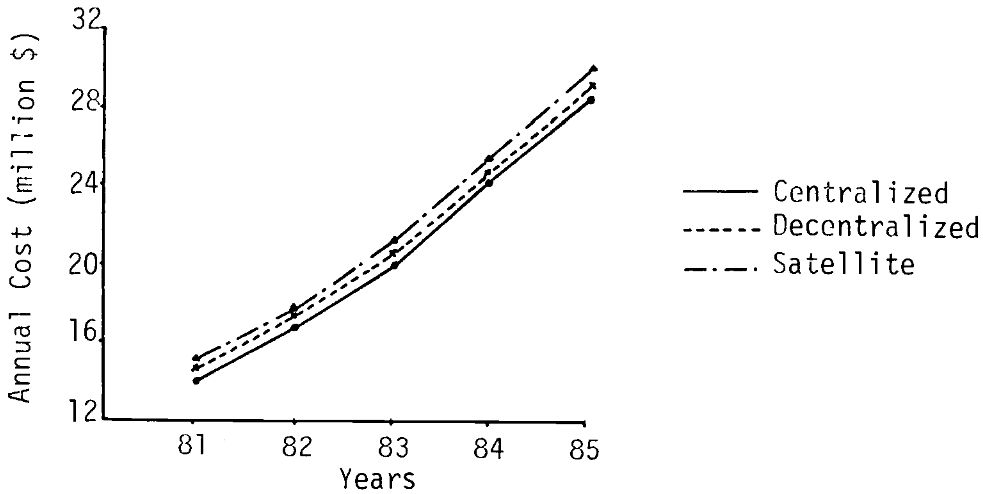


Figure 12. Annual cost for the three alternatives (20 percent annual growth rate).

The annual cost may now be used in the cash flow analysis to determine the present worth and, subsequently, the annual worth of the three alternatives. The present worth and annual worths for the three alternatives at 10 percent and 20 percent growth rates are shown in Table XXII.

TABLE XXII. ANNUAL WORTH AND PRESENT WORTH OF THE THREE ALTERNATIVES AT 10 PERCENT AND 20 PERCENT ANNUAL GROWTH RATES.

Mode of Operation	10% Growth Rate		20% Growth Rate	
	(all values in million $)			
	PW	AW	PW	AW
Centralized	36.25	14.88	46.00	18.89
Decentralized	37.47	15.38	47.12	19.34
Satellite	38.39	15.76	48.43	19.88

For both growth rates, the annual cost shows a preference for the centralized facility. Satellite production still carries the highest annual cost for both growth rates.

V. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

The objective of this study was to examine three different production alternatives for circuit board manufacture and to identify the alternative which results in maximum return on invested capital. The three alternatives examined were centralized production, decentralized production, and satellite mode of operation. This objective was accomplished by examining different cost parameters involved in printed circuit board manufacture, developing cost evaluation procedures for the cost factors which differ significantly between alternatives, and then reducing the cost figures to an equivalent annual worth for comparison purposes.

Conclusions

Results obtained from annual worth comparisons at 10 percent, 15 percent, and 20 percent annual growth rates all showed centralized production as the preferred alternative. These results are summarized in Table XXIII.

TABLE XXIII. ANNUAL WORTH FOR THE THREE ALTERNATIVES AT 10, 15, AND 20 PERCENT GROWTH RATES.

Growth Rate Per Annum (%)	Annual Costs (million $)		
	Centralized	Decentralized	Satellite
10	14.88	15.38	15.76
15	16.77	17.26	17.71
20	18.89	19.34	19.88

Analysis at all three growth rates showed the same trend--centralized production was the least expensive to invest in and operate; satellite production was the most expensive.

Cost evaluations for the three alternatives distinctly showed that centralized production requires the least amount of capital outlay and that the extra expenditure of capital in both satellite and decentralized facilities does not yield any savings in the operating, inspection, and maintenance costs to provide any economic justification.

In evaluating the cost parameters, some aspects of these costs have been neglected due to the unavailability of current data or difficulty in evaluating the necessary data for analysis in the short time available. One such aspect is the component of indirect cost accounting for overhead such as utilities; employee facilities such as cafeterias; and administrative expenses such as telephone, telegraph, and travel. The cost of these factors will also strongly favor centralized production, since operating facilities for decentralized and satellite arrangements will require more investment and maintenance in these overheads.

An additional advantage of having a centralized production facility will be a common pool of schedulers and programmers. Although development of programming and scheduling cost is beyond the scope of this study, a centralized facility will incur less cost in scheduling and programming. Each of the decentralized facilities will have to maintain a separate pool of schedulers and programmers besides substantially higher investment in computer hardware.

Of the factors quantified in this study, distribution cost is the only factor which favors decentralization. Even decentralized cost did not turn out to be as significant as some of the other cost parameters quantified in this study. This is because a distribution time of one day is assumed in evaluating distribution cost. This time is based on the current location of the business units at TEK and will increase significantly as the business units spread out, resulting in much higher distribution costs.

Of the intangible factors difficult to quantify, corporate strategy is an overriding factor in deciding which production alternative to adopt. A study conducted by Vancil and Buddrus (1979) showed that decentralization is the most common organizational mode in U. S. manufacturing corporations today; not only in large, diversified firms, but also in relatively homogeneous businesses with sales of $100 million or less. The benefits of decentralized management are apparently worth the costs.

The primary advantage of decentralized management lies in its potential for improving the quality of managerial decisions. For companies undergoing rapid expansion into new functions, new geographical areas, or new product lines, decentralization removes the top managers from the more routine operational activities and gives them the time, information, and even the psychological commitment for long-term planning and appraisal. At the same time, decentralization provides incentives and opportunities for young, potential managers by delegating authority and assigning responsibility.

Another intangible to be considered in deciding between alternatives is future expansion. In any progressive organization, expansion is inevitable. The need for expansion may come from any one of the number of reasons related to a need for additional volume, product, parts, processes, or services. An important factor in expansion is the cost of future space. The surroundings of a centralized facility location develop much more rapidly as compared to the surroundings of smaller, decentralized locations, resulting in a much higher hike in the price of land for a centralized facility. Another factor in future expansion is the disruption caused by the actual move. Decentralization provides more flexibility in that disruption caused in production at one facility does not affect production at other locations.

These unquantified factors are important considerations in deciding between alternatives. However, based on the factors quantified in this study, centralized printed circuit board manufacture is the preferred alternative resulting in least capital expenditure, smaller operating and maintenance costs, and higher machine and manpower utilization.

Recommendations for Future Research

This study examines centralized, decentralized, and satellite production alternatives. Another production alternative that may be applicable to this type of operation is the cell structure arrangement. Cell structure arrangements use the concept of "group technology".

According to Mahany and Tompkins (1977), group technology is a method of manufacturing piece parts by classification of these parts into groups and subsequently applying to each group similar technological operations. The major result of this method of manufacture is to obtain economics which are usually associated with large scale production in small scale situations and is, therefore, of fundamental importance in batch producing types of operations.

Division of production into cells results in less waiting and handling, simpler set up and tooling, and reduced in-process inventory. The biggest disadvantage is the if the volume does not justify independent cells, application of this method may result in low machine utilization and high capital investment.

The key to the application of group technology is the grouping of boards into families and then applying the manufacturing sequence to each family separately. Each family forms an independent cell with its own planning, scheduling, and control. The grouping of components into families may be based on the following methods, suggested by El Gomayel (1973) and Shunk (1973):

1. Classification by design features.
2. Classification by production features.
3. Production flow anaysis where routing sheets for components are studied, and components having some route are considered to form a family.
4. Grouping around critical machines; components with common critical machines form families.

In circuit board manufacture, classification by production features may be used to cut down on initial investment, particularly on the sequencers and the testing equipment. Board classification into families may be based on similar part numbers, which would substantially reduce the set up time on the sequencers and the testing equipment. A more sophisticated scheme of classification may take into account both the part numbers and the size of the board. This scheme may not only reduce sequencing and testing times, but may also cut down the set up time on the flow soldering machines (since set up time on the flow soldering machine depends on the change in the size of a board from one run to another).

The analysis in this study ignores inventory cost differences primarily because of the non-availibility of current and historical data on safety stocks, and the uncertainty on how to account for inflation in inventory stocks. Difference in inventory cost may be significant, depending upon the level of stocks carried at each facility and location of the facility. The management at TEK needs to formulate an inventory policy as to the levels of stocks to be maintained and the variations permitted in safety stocks due to inflation. Another factor that would be decided upon by the management is the location of the warehouse supplying circuit boards and components to the production line. The location will effect the inventory level to be carried in the warehouse and the distribution cost of raw material.

The time data for sequencing, component insertion, and hardware insertion is based on current machine capacities and limitations. An effort was made to test the variation of this data over time. However, no previous records were availible for testing the historical trends shown in the time data. Slight variations or modifications in machine design may substantially change the sequencing and insertion times. This change may alter machine requirements and utilization. It is recommended that the current time data be tested for its validity in the future and any trends be taken into consideration.

The set up and run times for sequencing obtained using the current sequencing data at TEK and the 0-1 integer programming model indicates that the set up time represents 33 percent of the total production time, as shown in Table XXIV.

TABLE XXIV. SET UP TIME AS PERCENTAGE OF TOTAL PRODUCTION TIME

Part Category	Percent Boards by Volume	Set Up Time as Percent of Total Production Time	Weighted Average
0-20	86.36	29.24	25.25
21-40	8.05	57.31	4.61
41-60	3.59	60.13	2.16
61-80	2.00	60.26	1.21
			33.23

The set up time can be substantially reduced by increasing the number of boards processed per run, i.e., economic order quantity.

An area which shows promise for a centralized facility is the possible application of a hierarchical computer control system. This concept starts with a single machine and builds up step-by-step to a high level of automation as the production requirements increase.

The first level of automation involves one computer for each machine. The individual machines may be sequencers, component inserters, or hardware inserters, each controlled by its own independently programmed mini-computer. Currently TEK is operating at this level of automation.

At the next level, a single computer, called a worker, controls a series of machines. Each worker computer simultaneously controls its machines and gathers management data. At the third level, a supervisor computer monitors the work of several worker computers. The supervisory computer performs three functions. First, it monitors the production of each of the worker computers and loads new programs into the workers when job requirements change, as, for example, when a run of a particular board is completed and a new run is set up to produce boards with a different arrangement of components. Secondly, it maintains a collection of as many as 1,000 of these pattern control programs on a directly accessible magnetic drum unit or other bulk storage unit which eliminates the need to program the workers individually from paper tapes. Thirdly, the system displays management data gathered by the workers and makes it availible for transmission to a distant data processing computer as required.

At the highest level, a management computer monitors multiple supervisory computers, each of which has a group of worker computers under it. In this system, automatic couputer-to-computer communications would permit any management computer to back up any failed supervisory computer, permitting the system to continue in operation at a reduced level, instead of shutting down altogether. The level of particular application depends on product configuration and annual output.

A Final Perspective

Improvements in productivity of the manufacturing sector has been a matter of major concern in the United States. The electronics industry is an important sector of manufacturing and within the electronics industry, insertion of circuit boards is a key activity. Improvements in productivity of circuit board manufacture may be achieved by replacing manual component insertion with automatic insertion. However, automatic insertion requires high capital expenditure; the capital must, therefore, be invested in production alternatives that will result in the largest productivity improvement for every dollar invested. A critical decision regarding capital investment in component insertion is centralized versus decentralized production.

This study has primarily been concerned with the problem of evaluating the economic feasibility of centralized circuit board manufacturing, decentralized circuit board manufacturing, and satellite production, which employs a mixed production strategy whereby machine insertion is centralized but all other operations involved in printed circuit board manufacture are decentralized.

The approach used in this study was to examine the different cost parameters involved in PCB manufacture and identify those factors which differ significantly between the three production alternatives, develop procedures for estimating these costs parameters, and then to use the annual worth basis to compare the three alternatives.

The methodology developed in this study was applied to analyse this problem for Tektronix, Incorporated. The analysis showed that, under the present production and economic conditions at TEK, centralized printed circuit board manufacture is the preferred alternative resulting in the least capital expenditure, smaller operating and maintenance costs, and higher machine and manpower utilization.

BIBLIOGRAPHY

1. Bridges, R. O., 1977. "Sequencing of Components for Automatic Assembly on Printed Wiring Boards", Western Electric Engineer, (U.S.A.), Vol. 21, No. 3, pp. 14-18.
2. Bump, E. A., 1974. "Effects of Learning on Cost Projections", Management Accounting, Vol. 25, No. 11, pp. 19-24.
3. El Gomayl, Y. I., 1973. "Group Technology and Computer Aided Programming for Manufacture", Transactions of the Society of Manufacturing Engineers, Paper #MS 73-980, p. 10.
4. Estes, C. B., W. C. Turner, and K.E. Case, 1980. "The Shrinking Value of Money and Its Effects on Economic Analysis", Industrial Engineering, Vol. 12, No. 3, pp. 18-22.
5. Francis, R. L. and J. A. White, 1974. Facility Layout and Location: An Analytical Approach, New Jersey, Prentice-Hall, Inc., p.468.
6. Freese, D. R., 1974. "Streamlining Insertion of Components on P.C. Boards", Electronics, (U.S.A.), Vol. 47, No. 18, pp. 117-123.
7. Hines, W. W. and D. C. Montgomery, 1972. Probability and Statistics, New York, The Ronald Press, Co., p. 509.
8. Kendrick, J. W., 1977. Understanding Productivity: An Introduction to the Dynamics of Productivity Change, Baltimore, John Hopkins University Press, p. 141.
9. Kirschenman, D. L., 1975. "Mechanised Insertion of Transistors in Printed Wiring Boards", Western Electric Engineer, (U.S.A.) Vol. 19, No. 1, pp. 19-23.
10. Mahany, H. M. and J. A. Tompkins, 1977. "GT and MRP: An Unbeatible Combination", Proceedings Systems Engineering Conference A.I.I.E., Kansas City, Missouri, Nov. 2-4, 1977, pp. 150-153.
11. McKee, K. E. and J. McGurk, 1979. "Manufacturing Productivity: The Challenge for the 1980's", Proceedings, Spring Annual Conference A.I.I.E., San Francisco, May 22-25, 1979, pp. 655-657.
12. Pericich, C. E., 1978. "Component Layout for Automatic Assembly", Circuits Manufacturing, (U.S.A.), Vol. 18, No. 1, pp. 54-58.
13. Richerson, M. E., 1976. "Computer Program Controls Component Sequencer Costs", Assembly Engineering, Vol. 19, No. 12, pp. 24-27.
14. Riggs, J. L., 1978. "Productivity Perspectives: Consideration for Economic Analysis", Proceeding Spring Annual Conference and Productivity Engineering Show, A.I.I.E., Toronto, Canada, May 23-26, 1978, pp. 50-54.
15. Riggs, J. L., 1977. Engineering Economics, New York, McGraw-Hill, Inc., p. 617.
16. Riggs, J. L., 1980. "Inflation, Taxes, and Other Economic Frustrations in the Justification of Material Handling and Investment", Proceedings A.I.I.E./Material Handling Institute Conference, San Francisco, Mar. 1980.
17. Shunk, D. L., 1973. "A Look at the Effect of GT", Transactions of the Society of Manufacturing Engineers, Paper #MM73-127, p. 11.
18. Snedecor, J. W. and W. G. Cochran, 1978. Statistical Methods, Ames, Iowa, The Iowa State University Press, p. 593.

19. Thompson, T., 1977. "Fast, Low-Cost, Semiautomatic Component Insertion Machines", Assembly Engineering, Vol. 20, No. 11, pp. 36-39.
20. Titlebaum, R. P., 1976. "An Insertion Machine for Everyone, Almost Part I", Assembly Engineering, Vol. 19, No. 8, pp. 34-39.
21. Titlebaum, R. P., 1976. "An Insertion Machine for Everyone, Almost Part II", Assembly Engineering, Vol. 19, No. 9, pp. 36-39.
22. Towill, D. R., 1976. "Transfer Functions and Learning Curves", Ergonomics, Vol. 19, No. 5, pp. 623-638.
23. Vancil, R. F. and L.E. Buddrus, 1979. Decentralization: Managerial Ambiguity by Design, New York, Financial Executives Research Foundation, p. 393.
24. Wilkinson, K., 1975. "Computers in Electronics Design", Electron and Power, (Great Britain), Vol. 21, No. 11, pp.684-685.

APPENDIX A

SUMMARY OF DATA USED IN THE ANALYSIS

A-I. TIME STANDARDS

Operation	Insertion (or Testing) Time per Board (hrs)	Percentage of Boards by Volume Undergoing Operation (%)
Component Insertion	0.0183	86.78
Hardware Insertion	0.0182	95.00
Hand Insertion	0.2812	74.52
Flow Soldering, In-line Cleaning	0.0196	74.52
Straightening, Hand Adds, Finishing	0.3879	98.01
Lead Clipping	0.0153	60.34
Transistorising	0.1804	65.26
Inspection	0.0996	98.01
Exploded Testing	0.25	100.00
In-circuit Testing	0.0286	70.00
Functional Testing	0.0769	21.00

A-II. MACHINE UTILIZATION

Equipment	Percent Utilization (%)
Sequencer	84.98
Component Inserter	89.79
Hardware Inserter	90.00
Flow Soldering Machine	85.00
Automatic Testing Equipment	90.00

A-III. FIRST COSTS OF EQUIPMENT (INCLUDES INSTALLATION AND FREIGHT)

Equipment	First Cost ($)
Sequencer	
20-station basic module	42,000
20-station additional module	15,750
Component Inserter (Single Head)	68,250
Hardware Inserter	52,500
Flow Soldering Machine (Electrovert)	105,000
Exploded Tester	15,000
In-circuit Tester	125,000
Functional Tester	300,000

A-IV. OPERATING COSTS (DOES NOT INCLUDE PAY BENEFITS)

Unit	Annual Cost ($/yr)
Sequencer	11,440
Component Inserter	10,590
Hardware Inserter	9,080
Flow Soldering Machine	10,590
Exploded Testing	12,350
Automatic Testing	10,590
Kit Prep	9,810
All Manual Operations (except Kit Prep)	10,590
Supervisory Managers	21,170
Maintenance Managers	16,800
Maintenance Technicians	14,410

A-V. Miscellaneous Data

1. Benefits are 20 percent of base salary.

2. In automatic testing, the first pass yield is 70 percent, the second pass yield is assumed to be 100 percent.

3. Labor turnover rate is assumed to be 40 percent per annum. This rate does not represent the actual turnover at TEK.

4. Adminstrative cost associated with hiring is estimated at $500 per new employee (personnel department).

5. In evaluating distribution cost, the average distribution time for the boards is one day, interest on tied up capital is 30 percent.

A-VI. Sources of Data

The data used in this analysis was collected from various sources at Tektronix, Incorporated.

1. Computer schedules obtained from the Manufacturing Industrial Systems Support Group provided information concerning annual board demand, insertable boards, components and part numbers per board, and insertion times for the component inserter.

2. Computer report for February, 1980, obtained from the Centralized Machine Insertion area provided information regarding sequencing and hardware insertion times.

3. Maintenance records for the period April, 1979 to December, 1979 were used to evaluate equipment utilization.

4. Data pertaining to all hand operations was obtained from the current MTM standards used by the Communications Division and from a report prepared by the Manufacturing Engineering Systems Group (January, 1979) for COM Division.

5. Cost and time data for automatic testing equipment was obtained from the Information Display Division.

APPENDIX B

EQUIPMENT AND MANPOWER REQUIREMENTS AT 15 PERCENT ANNUAL GROWTH RATE

B-I. CENTRALIZATION

Operation	Requirements 1981	1982	1983	1984	1985
Sequencer	11	13	15	17	17
Component Insertion	14	16	19	22	25
Hardware Insertion	16	18	20	23	27
Kit Prep	257	296	340	391	449
Hand Insertion	165	190	218	251	288
Flow Soldering	14	16	18	21	24
Hand Adds	299	344	395	454	522
Lead Clipping	8	9	10	12	13
Transistorising	93	107	123	141	162
Inspection	77	89	102	117	134
Exploded Testing	218	251	289	332	382
In-circuit Testing	23	27	30	35	40
Functional Testing	19	22	25	28	32

B-II. DECENTRALIZATION

Operation	Requirements 1981	1982	1983	1984	1985
Sequencer	11	13	16	17	18
Component Insertion	16	18	21	23	26
Hardware Insertion	17	19	21	25	28
Kit Prep	258	297	340	392	451
Hand Insertion	166	191	220	251	290
Flow Soldering	16	18	20	23	26
Hand Adds	300	345	396	457	523
Lead Clipping	10	11	11	13	14
Transistorising	94	108	124	143	164
Inspection	78	90	103	117	136
Exploded Testing	221	259	290	333	383
In-circuit Testing	24	28	31	36	41
Functional Testing	20	24	26	29	34

B-III. SATELLITE

Operation	Requirements 1981	1982	1983	1984	1985
Sequencer	11	13	15	17	17
Component Insertion	14	16	19	22	25
Hardware Insertion	16	18	20	23	26
Kit Prep	258	297	340	392	451
Hand Insertion	166	191	220	251	290
Flow Soldering	16	18	20	23	26
Hand Adds	300	345	396	457	523
Lead Clipping	10	11	11	13	14
Transistorising	94	108	124	143	164
Inspection	146	168	193	221	255
Exploded Testing	221	259	290	333	383
In-circuit Testing	24	28	31	36	41
Functional Testing	20	24	26	29	34

APPENDIX C

PRODUCTION REQUIREMENTS AND ANNUAL COSTS AT 10 PERCENT ANNUAL GROWTH RATE

C-I. TOTAL BOARD REQUIREMENTS

Mode of Operation	Total Board Requirement/Yr 1981	1982	1983	1984	1985
Centralized	2,627,478	2,890,225	3,179,248	3,496,934	3,845,672
Decentralized					
IDD	425,791	468,370	515,208	566,690	623,204
COM	376,870	414,557	456,013	501,580	551,601
SID	787,552	866,307	952,937	1,048,160	1,152,689
LID	1,037,265	1,140,991	1,255,090	1,380,505	1,518,178

C-II. INSERTABLE BOARD REQUIREMENTS

Mode of Operation	Insertable Board Requirement/Yr 1981	1982	1983	1984	1985
Centralized	2,280,027	2,508,030	2,758,833	3,034,509	3,337,131
Decentralized					
IDD	406,258	468,370	515,208	566,690	623,204
COM	264,155	290,571	319,628	351,566	386,627
SID	719,243	791,167	870,284	957,247	1,052,710
LID	890,372	979,409	1,077,350	1,185,004	1,303,181

C-III. ANNUAL COSTS

Costs	Annual Costs (million $) for Centralized Facility 1981	1982	1983	1984	1985
Machine	6.22	6.86	7.57	8.28	8.99
Direct Labor	4.87	5.36	5.90	6.49	7.14
Inspection	0.47	0.52	0.57	0.62	0.68
Training	0.27	0.29	0.32	0.35	0.39
Indirect	0.74	0.81	0.90	0.99	1.08
Maintenance	0.23	0.25	0.27	0.29	0.31
Distribution	0.014	0.015	0.017	0.019	0.020
TOTAL	12.81	14.10	15.54	17.04	18.61

Costs	Annual Costs (million $) for Decentralized Facility 1981	1982	1983	1984	1985
Machine	6.61	7.22	7.94	8.61	9.50
Direct Labor	4.92	5.41	5.96	6.51	7.18
Inspection	0.47	0.53	0.57	0.63	0.70
Training	0.27	0.29	0.33	0.36	0.39
Indirect	0.77	0.85	0.93	1.02	1.12
Maintenance	0.27	0.28	0.31	0.33	0.36
Distribution	(no distribution cost is incurred)				
TOTAL	13.31	14.58	16.04	17.46	19.25

Costs	Annual Costs (million $) for Satellite Production 1981	1982	1983	1984	1985
Machine	6.47	7.11	7.87	8.50	9.33
Direct Labor	4.92	5.41	5.96	6.52	7.18
Inspection	0.88	0.99	1.07	1.18	1.30
Training	0.29	0.31	0.34	0.38	0.41
Indirect	0.79	0.86	0.97	1.05	1.16
Maintenance	0.24	0.26	0.28	0.30	0.33
Distribution	0.0016	0.0017	0.0019	0.0020	0.0022
TOTAL	13.59	14.94	16.49	17.93	19.71

APPENDIX D

PRODUCTION REQUIREMENTS AND ANNUAL COSTS AT 20 PERCENT ANNUAL GROWTH RATE

D-I. TOTAL BOARD REQUIREMENTS

Mode of Operation	Total Board Requirements/Yr 1981	1982	1983	1984	1985
Centralized	2,866,339	3,439,607	4,127,528	4,953,990	5,947,654
Decentralized					
IDD	464,500	557,400	668,879	802,810	963,837
COM	411,131	493,357	592,028	710,571	853,096
SID	859,147	1,030,977	1,237,172	1,484,893	1,782,730
LID	1,131,562	1,357,874	1,629,449	1,955,716	2,347,990

D-II. INSERTABLE BOARD REQUIREMENTS

Mode of Operation	Total Board Requirements/Yr 1981	1982	1983	1984	1985
Centralized	2,487,302	2,984,763	3,581,715	4,298,888	5,161,152
Decentralized					
IDD	443,190	531,828	638,194	765,980	919,619
COM	288,169	345,803	414,964	498,052	597,951
SID	784,628	941,554	1,129,865	1,356,099	1,628,104
LID	971,315	1,165,578	1,398,693	1,678,756	2,015,478

D -III ANNUAL COSTS

Costs	Annual Costs (million $) for Centralized Facility 1981	1982	1983	1984	1985
Machine	6.83	8.07	9.74	11.71	13.90
Direct Labor	5.32	6.38	7.65	9.19	11.03
Inspection	0.51	0.61	0.74	0.88	1.06
Training	0.29	0.35	0.42	0.50	0.60
Indirect	0.81	0.98	1.16	1.40	1.68
Maintenance	0.25	0.28	0.35	0.41	0.48
Distribution	0.015	0.018	0.022	0.026	0.031
TOTAL	14.03	16.68	20.08	24.12	28.78

Costs	Annual Costs (million $) for Decentralized Facility 1981	1982	1983	1984	1985
Machine	7.20	8.56	10.05	11.98	14.19
Direct Labor	5.36	6.42	7.70	9.22	11.07
Inspection	0.52	0.62	0.74	0.89	1.06
Training	0.29	0.35	0.42	0.50	0.60
Indirect	0.85	0.99	1.21	1.44	1.72
Maintenance	0.27	0.33	0.38	0.44	0.51
Distribution	(no distribution cost incurred)				
TOTAL	14.49	17.27	20.50	24.47	29.15

Costs	Annual Costs (million $) for Satellite Production 1981	1982	1983	1984	1985
Machine	7.09	8.42	9.93	11.93	14.08
Direct Labor	5.36	6.42	7.71	9.23	11.07
Inspection	0.97	1.16	1.39	1.67	2.00
Training	0.31	0.37	0.44	0.53	0.63
Indirect	0.86	1.04	1.23	1.49	1.78
Maintenance	0.25	0.31	0.35	0.43	0.49
Distribution	0.0017	0.0020	0.0024	0.0029	0.0033
TOTAL	14.84	17.72	21.05	25.28	30.05