THE

PRINTED CIRCUIT BOARD

ASSEMBLY AND TEST OPERATION:

TOWARD A BETTER PROCESS

by

JAMES FRANCIS REDA

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Signature of Author: _____
Sloan School of Management, May 16, 1983

Certified by: _____
Gabriel R. Bitran
Thesis Supervisor

Accepted by: _____
Jeffrey A. Barks
Director of Master's Programs

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ABSTRACT

A field study was carried out at a computer system
manufacturer. A capacity expansion project directed toward
reducing work-in-process (WIP) inventory, while at the same
time reducing the prime cost of manufacturing, was being
undertaken by the company under study. The object of the
capacity expansion project is the printed circuit board
(PCB) assembly and test operation. A PCB is a sturdy,
electrically non-conductive platform on which electronic
and hardware components are mounted.

The intent of the capacity expansion project is to reduce
the manufacturing cycle time of the PCB assembly and test
operation from six weeks to one week. With this reduction,
many advantages follow. The main advantages are an
increased rate of inventory turn-over, and lower prime
manufacturing costs. As part of the capacity expansion
project, the assembly operation was re-organized. This
re-organization should further lower the prime
manufacturing costs.

As a result of the reduction in WIP inventory and the
re-organization of assembly operation, the task of
production scheduling becomes much more difficult.

Thesis Supervisor: Dr. Gabriel R. Bitran

    Title: Professor of Operations Management

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Introduction

Having worked in the computer systems manufacturing industry, I noticed that computer systems are built by batch production methods. Not only are the computer system components built by batch production methods, but they are also built in relatively small lots. This manufacturing environment promotes a great amount of work-in-process (WIP) inventory to accumulate. A reduction in WIP inventory translates into a reduction of investment in inventory, and thus less costs, and more profit-before-taxes to the firm. The only way to reduce WIP inventory is to reduce the the cycle time needed to manufacture the product; the only way to reduce cycle time is to increase the capacity of the manufacturing facility.

Since computer manufacturers can save money, some manufacturers are exploring ways to increase capacity, while at the same time maintaining, or reducing the levels of operating cost. In this thesis, I will detail one computer manufacturer's attempt at reducing the manufacturing cycle time of the printed circuit board (PCB) assembly and test (A & T) operation. Of all the manufacturing operations necessary to build a computer system, the printed circuit board assembly and test operation is a good candidate for a capacity expansion project.

A printed circuit board (PCB) is a sturdy, electrically non-conductive platform on which electronic and hardware components are mounted; PCB's are the building blocks of most computer systems. This thesis will center on approaches that may be used to increase the capacity of the PCB assembly and test operation.

Many benefits will follow from this capacity expansion project. In addition to lower operating costs, lower allocated overhead costs via a lower working capital requirement should result from this project.

A secondary strategy of this capacity expansion project is to reduce the ambiguity of fabricating, assembling, testing, and integrating the PCBs into a computer system. If the ambiguity of the process is lessened, the source of production problems will become more apparent, and thus, easier to correct.

From that normative model, financial benefits came, and if indeed an ideal model emerges, production flexibility will also emerge. An ideal model of the assembly and test operation will allow for wide changes of product mix with no significant changes in operating costs, quality of finished products, or the time to assemble and test a PCB. Furthermore, this ideal model should allow quick changes to be made to the existing product and short time spans to introduce a new product to the assembly and test operation.

If reducing the time to build a computer without increasing operating costs can save money, why hasn't it been done before? In short, much work has been done to reduce the manufacturing cycle time; however, it is not a simple task. Capacity expansion programs tend to disrupt manufacturing operations. Moreover, they are accomplished by increasing the capital base and reducing the labor base. Both of these actions are unattractive. The first one introduces a risk that the forecasted demand used to justify the capital expenditure will not materialize, thus causing the capital surcharge on each unit of output to increase above profitable levels. The second action causes a relocation of labor at best, and layoffs of labor at worst. Most computer system manufacturers attempt to avoid layoffs of the labor force.

Given the competitive nature of the computer systems industry, manufacturers have no choice but to reduce operating costs, and to improve customer service. Previously, computer system manufacturers commanded high prices in the market place for their product. As a result, little attention was paid to the costs of manufacturing; companies competed strictly on electronic functionality. However, recently, profit margins for computer systems have been lowered. This has caused computer system manufacturers to look inward, with the idea to reduce operating costs, improve customer service, and thus

maintain their degree of profitability. At least two large
mid-sized computer manufacturers have begun to undertake
large-scale work-in-process inventory reduction projects.
This thesis will detail the efforts of one of these
companies.

To date, there have been great strides made in PCB
assembly and test operation capacity expansion projects.
As a result of efforts towards automation, less time and
cost is required to assemble and test PCB's. Improvements
such as the following have reduced the time and cost of
assembling and testing PCB's in a high production volume
environment by:

> 1. replacing hand soldering with automatic
> soldering;
> 2. replacing electronic bench testing with
> automatic testing;
> 3. replacing hand electronic component insertion
> with automatic insertion.

All three improvements have replaced human efforts with
those of a machine. Furthermore, all three improvements
have increased capacity, while costs of manufacturing have
at least remained the same.

Other industries have made similar attempts to reduce work-in-process inventory. In these cases, batch production methods were substituted by continuous production methods. Industries such as automobile and glass have been successful at reducing their working capital requirements. Capacity additions were paid for by reduced operating costs.

In the early 1900's, Henry Ford devised the assembly line for manufacturing automobiles. In the 1920's, Pilkington Glass Company devised a process to make sheet glass by a continuous method. In the 1950's, Ford converted its engine block machining facility into a continuous process. In all three cases capacity was increased, unit costs of production were decreased, and the time to build a unit of product reduced (Abernathy,2).

To accomplish this study, I will first describe the computer systems industry in chapter one. Then, in chapter two, I will describe the existing PCB assembly and test operation at the company under study. Chapter three will describe a portion of the manufacturing cycle time in mathematical terms. In chapter four, issues inherent to the assembly and test operation will be discussed.

Next, in chapter five, a normative model of the PCB assembly and test operation will be described. This normative model will use technology that is available today, or technology that will available in the near future. The intent of this normative model will be to increase the productive capacity of the PCB assembly and test operation without increasing the costs of manufacturing. Chapter six will discuss the advantages, and disadvantages of the normative operation as compared to the descriptive (present) operation. In addition, chapter six will discuss the transition from the descriptive to the normative operation. Chapter seven will draw conclusions from the study.

Literature Search

On searching the literature, I could not find any
discussion of the modernization of the assembly and test
operation, neither descriptive nor analytical.
Furthermore, in general, little or no material exists as to
the automation of the computer system manufacturing
operation. Most of the specific literature is authored by
salesmen from the equipment suppliers (Universal,14); this
literature does not project the multi-disciplinary approach
necessary to automate the assembly and test process.

Numerous articles appear in publications such as
Production Engineering (4,8) outlining the automation
taking place in industries that use metal cutting as their
primary manufacturing process. A similarity exists between
the automation of the metal cutting industry and the
automation of the computer system manufacturing industry.
However, the similarity decreases the closer the discussion
is to the production floor and the product. Only issues
such as managerial implications or cost accounting changes
precipitated by a major process change can be discussed
when comparing an assembly and test operation with a metal
cutting operation (Gerwin,5).

At the 1983 National Material Handling Show (NHMS), an automated electronic equipment production facility was displayed (Thames,13). The exhibit displayed an automated production facility that manufactures power supply modules. The mock-up of a production facility will automatically insert components into a PCB; all the production machines are linked to one another via an optical-fiber cable. Unlike the assembly and test operation in the computer system manufacturing industry, which must be able to accommodate hundreds of different PCB's, the NHMS exhibit manufactures only three relatively simple PCB's.

At the 1983 Chicago Trade Show, robots made by International Business Machines assembled PCB's (Shaffer,12). Yet, robots are certainly not widely used in the PCB assembly and test operation of today.

Chapter 1: Background Information

1.1 COMPUTER SYSTEMS INDUSTRY

As time passes, the computer systems industry is becoming more competitive. This competition manifests itself in shorter product life, less time between new product introductions, and slimmer profit margins. Furthermore, when one competitor announces a product breakthrough, the time to capitalize on the comparative advantage has lessened. As a result of this increased competition, the manufacturing function has been stimulated to introduce new products faster into the market place, and to attain high production volumes of this new product quickly.

The price of a computer system is determined in the marketplace. Thus, any savings experienced in operating costs, is an extra dollar of pre-tax profit. In the early to mid 1970's, there were many highly cost effective applications for mid-sized computers. At the same time, there were few companies manufacturing mid-sized computers. As a result, these few manufacturers could demand high prices in the market place, and thus high profit margins. In the 1980's, the number of cost effective applications remaining to be computerized has not increased, while the number of computer manufacturers has increased. Furthermore, the function of a mid-sized computer of the

early to mid 1970's can be had by purchasing a smaller, less expensive business computer of the 1980's. Thus, the profit margins of the mid-size computer manufacturers have been squeezed.

1.2 ROLE OF A PCB WITHIN A COMPUTER SYSTEM

The PCB is a sturdy, electrically non-conductive platform on which electronic and hardware components are mounted. The function of a PCB is determined by what components are used, and how these components are connected to each other. The PCB provides a stable mechanical platform so that the electrical connections between the components remain intact at all times. PCB's range in size from 1 by 2 inches to 15 by 15 inches or larger.

A typical computer system is composed of many system components. The PCB is the building block of these system components. Most computer systems are comprised of approximately eight to fifteen printed circuit boards (PCB's), with two to six of these PCB's making up the central processing unit (CPU) or the heart of the computer system. Disc drives, power supplies, and CPU's all use PCB's. It is these PCB's which give the system component, and therefore the computer system, the unique electronic characteristics that that the end-user is seeking.

The Disc drives, power supplies, printed circuit boards, central processing units, cables, documentation, and cabinets are manufactured at either separate parts of a plant, separate plants, or purchased from a vendor (see Exhibit One). Once the system components are manufactured, they are integrated together to form a computer system. The process of integration happens either at another manufacturing facility, a customer site, or most commonly both at another plant and at the customer site. Although, in recent years more system integration is taking place at the site of the customer.

Before a PCB is assembled, it must be fabricated. The fabrication process uses epoxy resin, copper, precious metals, and various chemicals. Most computer systems manufacturers do not fabricate their own PCBs. Rather, they vend the operation to other companies, as the process is relatively straightforward and requires totally different equipment and labor skills than the assembly or test operation requires.

In the manufacturing organization, a distinction is made between the assembly and test operations. Even if the assembly and test operations are not organizationally distinct, the different operations require a different portfolio of skills to perform. Most manufacturers use specialized personnel to test the PCBs, and some manufacturers use production assemblers to repair the PCBs

in the final test and repair operation.

1.3 REASONS FOR LONG MANUFACTURING CYCLE TIME

There are three main reasons for the long
manufacturing cycle time. First, out of the six work
centers that the PCB visits in the assembly and test
operation, two are constrained by machine and labor
capacity. Second, out of the six weeks it now takes to
assemble and test a PCB, a certain amount of that time is
spent in a queue waiting for raw material. Third, the work
is not balanced between the six work centers in the
assembly and test operation.

Even if the work load was spread evenly throughout all
six work centers, and each work center was not
over-utilized, the raw material must be available when
needed to achieve a minimum cycle time.

1.4 DECOMPOSITION OF MANUFACTURING CYCLE TIME

The only way to decrease the WIP inventory levels is
to reduce the manufacturing cycle time. The manufacturing
cycle time is comprised of two parts:
- process time;
- and waiting time.

For the purposes of this thesis, process time includes the time to set-up an operation. In sum, the process time consists of two portions: a fixed and a variable portion. I use the terms fixed process time and set-up time interchangeably throughout the thesis. Waiting time is the time a PCB resides in a queue. In other words, waiting time is the difference between the manufacturing cycle time and the process time. Any technique that that would reduce the process or waiting times, would increase capacity and decrease WIP inventory.

Out of the six weeks necessary to build a batch of PCB's, the batch is being worked on approximately five percent of the time. The remaining portion of the six week period, the PCB's are sitting in a queue waiting to be worked on. The ratio of variable process time to manufacturing cycle time is not unlike a typical multiple work center operation (Gunn,7).

Since the waiting time is much greater than the process time, it is a more promising candidate for reduction. Perhaps to reduce the waiting time, better scheduling methods and better availability of raw materials are needed. More to the point, a large portion of the waiting time is due to the fact that two of the work centers do not have enough capacity to handle the work load at hand. These work centers are automatic DIP insertion, and final test and repair.

1.5 MEASUREMENT CRITERIA

Before the descriptive PCB assembly and test operation
is described, I will outline measurement criteria that can
be used to measure the performance of a PCB assembly and
test operation.

Three criteria can be used to measure performance of
the assembly and test operation:

- cost of manufacturing;
- electronic performance of PCB at the system
  integration level;
- manufacturing cycle time.

There are other criteria such as the adaptability of
the operation to a change in existing product, or the
adaptability of the operation to an introduction of a new
product; however, these criteria are hard to discuss on an
objective basis. Consequently, the discussion of these two
criteria will be limited.

The cost of manufacturing is, of course, a major
concern to the computer system manufacturer. Approximately
70 percent of the cost of manufacturing is put towards raw
materials. Out of that 70 percent, only a small fraction
is due to scrap. Thus, no real savings can be attained in
the area of raw materials by a manufacturing efficiency
project.

The other 30 percent is divided as follows:

- 15 percent direct labor;

- 10 percent for factory overhead;

- 5 percent for corporate overhead.

The capacity expansion should not cause any degradation in the electronic performance of the PCB's. If it does, additional costs will be incurred downstream of the PCB A & T operation.

As was discussed previously, the capacity expansion project should reduce the manufacturing cycle time. In brief, the advantages of such a reduction are as follows:

- reduction in customer order cycle time;

- less exposure to Engineering Change Orders;

- less investment in inventories.

These advantages will be discussed in chapter six.

Exhibit One

Computer Systems Manufacturing Operation

Integrated Circuit Packages

Printed Circuit Boards

Raw Material
(Electronic Components
and Hardware)
Inventory

Vendors

Assembly of Raw
Material

Vendors

Final Test

Central Processing
Units

Power Supplies

Signal Cable

Cabinet

Computer System
Integration

Disc Drive
Controllers

Disc Drive

Printer

Equipment
Documentation

Software
Programs
and
Documentation

Customer

Chapter 2: Descriptive Assembly and Test Operation

In this chapter I will describe the details of PCB assembly and test operation.

Before I discuss the three operations necessary to assemble and test a PCB, I will discuss the materials control aspect of the assembly and test operation.

2.1 MATERIALS CONTROL REQUIREMENTS

For purposes of material control, all raw material is received into the stock room area before it is released to the production floor. Then, depending on the type of raw material, a predetermined inspection is performed on the item. If the shipment of raw material passes inspection, it is prepared to be issued to the production floor. If the raw material shipment fails inspection, it is set aside to be returned to the vendor.

The time and effort spent inspecting raw material may significantly reduce the time and effort it takes to assemble and test a PCB. Once raw material is released to the production floor, and work has begun on it, it is very difficult to separate assembly-related-defects from supplier-related-defects.

The printed circuit board assembly and test process requires that the PCB visit six work centers (see Exhibit Two). These six work centers can be grouped into three distinct operations. These three operations are as follows:

1. component insertion;

2. solder and wash;

3. final test and repair.

Now, I will explain how these three operations are being performed. Some of these explanations are, indeed, very detailed; however, the detail will be needed to understand the evaluation of the normative operation.

2.2 COMPONENT INSERTION OPERATION

Approximately eighty percent of all components are inserted by an automatic inserter machine (Thames,13). The three main classification of automatic inserter machine are Dual In-line-Package (DIP), Variable Center Distance (VCD), and Single In-line-Package (SIP). The DIP machine inserts components that have pins on both sides of the rectangular body of the component. The VCD machine inserts components that have two in-line leads protruding from the component. The SIP machine inserts components that have pins protruding on the bottom-side of the component. Moreover, there are special machines that will insert pins, eyelets

and rotary components such as transistors onto the PCB.

To insert each class of component onto the PCB, the PCB is routed to each class of machine. In the descriptive operation, the routing sequence is simple. The first machine the PCB visits is a DIP inserter. Then, the PCB visits a VCD inserter. And finally, if necessary, the PCB is routed to a SIP and/or special class of machine (see Exhibit Three).

The set-up procedure for a DIP automatic inserter consists of three steps: load raw material, load insertion head path program, and align insertion head. To set-up the DIP inserter machine, the operator matches a channel of the machine to a "tube of IC's," as per manufacturing specifications. Once this is done, a program is loaded into the memory of the machine controller. This program contains step-by-step instructions as to the path of the insertion head. These instructions are loaded into the inserter's control computer by either paper-tape or magnetic disk. Finally, the operator guides the insertion head over the exact location where the first component is to be inserted. If this alignment is not correct, all subsequent insertions will not be on target.

The procedure to set-up a VCD inserter is the same as a DIP inserter except that reels of sequenced axial components are loaded into the machine in place of the tubes of IC's (Thames,13).

Depending on the class of machine, the whole set-up procedure requires approximately 17.5-30 minutes (see Table Two). I chose not to include the SIP or special classes of machine in this discussion, since not all PCB's require the use of these machines. After the machine is set-up, a batch of PCBs are processed. The average number of PCB's in a batch is approximately ten, in the company under study.

As was said before, ICs are inserted by the DIP (Dual In-line Package) Machine first. Then, the VCD (Variable Center Distance) Machine inserts the axial components (resistors, capacitors, etc.). Then the PCB is routed to the manual insertion area where components that are awkward to insert by machine are inserted by hand (see Table Two).

Out of the piece parts that are inserted, some are non-standard parts, which cannot be easily inserted by machine. Consequently, the production worker must refer to a manufacturing instruction for guidance as to what has to be done to the PCB. At the end of the component insertion operation, the PCB is prepared to be soldered by placing it into a frame. The frame provides mechanical stability to the PCB as it enters the wave of solder.

2.3 SOLDER AND WASH OPERATION

The PCB is conveyed over a wave of solder. In total, each conductive element of the PCB remains immersed in the solder for approximately four seconds. The speed of the conveyor, which transports the PCB over the wave of solder, is set anywhere from three to eight feet per minute. At the slow end of the operating spectrum - three feet per minute - the machine can solder large 15 by 15 inch PCB's in twenty-five seconds (0.416 minutes) (15/36=0.416).

In sum, the wave-solder machine is a fast, efficient method of soldering the large, densely populated PCBs of today's computer systems. Since the wave-solder is so quick and efficient, as many components as possible should be soldered by this method. Otherwise, the components not automatically soldered will have to be inserted, and soldered by hand.

2.4 FINAL TEST AND REPAIR OPERATION

Before a PCB can be verified as being built to engineering design specifications, it must be first subjected to a series of three electronic tests. The three electronic tests are as follows (see Exhibit Four):

1. electrical open/short;

2. component;

3. functional.

The electrical open/short test determines whether the
node-to-node path resistance is unusually high or low
towards electric current. Before any further electronic
tests can be performed, all electrical shorts must be
cleared by a repair technician. If the electrical shorts
are not cleared when full electrical power is applied,
excessive current may be drawn by the PCB. Not only would
this present a safety hazard, but it would also cause
extensive damage to the PCB.

After the electrical/shorts test is complete, the
components test then follows. At this level of test, the
component specifications are measured and compared with the
engineering specifications . If these measurements do not
match with the engineering design specifications, the
components are replaced by a repair technician. If all the
components are within specifications, the PCB should
perform its designed function.

To ensure that the PCB does perform its designed
function, the last test in the sequence of three electronic
tests - the functional test - is performed. The PCB is
effectively placed in its working environment, and stepped
through various exercises. If the desired performance is
not achieved, the PCB is routed to the repair area, where a
repair technician, with the aid of a printout generated by
the Automatic Test Equipment (ATE), finds the fault and

repairs the PCB.

.

Table One

Direct Labor Times for Descriptive A & T Operation
(minutes)

Operation	Set-Up	Variable	Total
A. Component Insertion	52.5	105	157.5
B. Solder and Wash	10	8	18
C. Final Test	12.5	280	292.5
Totals	75.0	393	468.0

Note: 1. Table is based on the assembly and test of a typical PCB. A typical PCB consists of the following:
- a. 205 total components
- b. 140 DIP components
- c. 60 Axial components
- d. Batch of ten PCBs
- e. 3 seconds per insertion
- f. 165 components auto-inserted
- g. 40 components hand-inserted
- h. 5 components are hardware
- i. 20 seconds per hand insertion
- j. 10 seconds per hand soldering

2. The preparation time of piece parts for the assembly operation does require considerable time. Due to the wide variance of this activity, it is not included.

3. Assembly Time = 175.5 minutes per batch of ten PCB's.

Table Two

Direct Labor Times for Descriptive
Component Insertion Operation
(minutes)

Work Center	Set-Up	Variable	Total
1. DIP Inserter	30	45	75
2. VCD Inserter	17.5	30	47.5
3. Manual Insertion	5	30	35
Totals	52.5	105	157.5

Note: 1. Time to sequence axial components varies with PCB.
However, since sequencing of axial components can
be done in parallel with other operations, this
step is not included in analysis.

2. See Note 1 below Table One.

Exhibit Two

Work Flow Diagram of PCB A & T Operation

```
        ┌─────────────────┐
        │  Raw Materials  │
        │    Inventory    │
        └────────┬────────┘
                 │
                 ▼
        ┌─────────────────┐
        │    Component    │
        │    Insertion    │
        └────────┬────────┘
                 │
                 ▼
        ┌─────────────────┐
        │   Solder and    │
        │      Wash       │
        └────────┬────────┘
                 │
                 ▼
        ┌─────────────────┐
        │  Final Test and │
        │     Repair      │
        └────────┬────────┘
                 │
                 ▼
        \─────────────────/
         \  Sub-Assembly /
          \  Inventory  /
           \───────────/
```
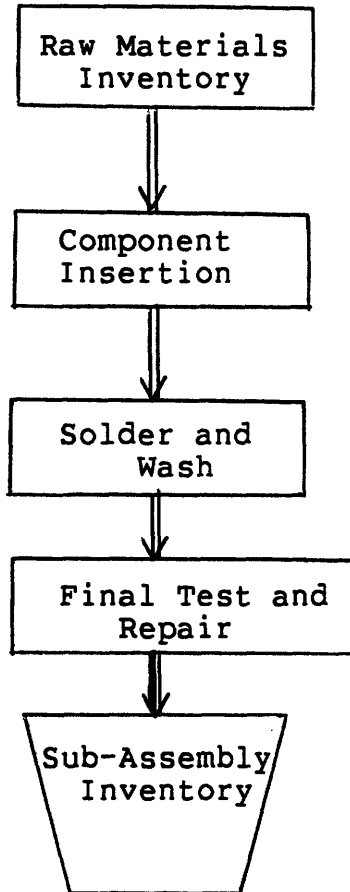
Note: 1. Component insertion operation consists of three
         work centers.

      2. Solder and wash operation consists of two
         work centers.

      3. Final test and repair operation consists of
         one work center.

Work Flow Diagram of Component Insertion Operation
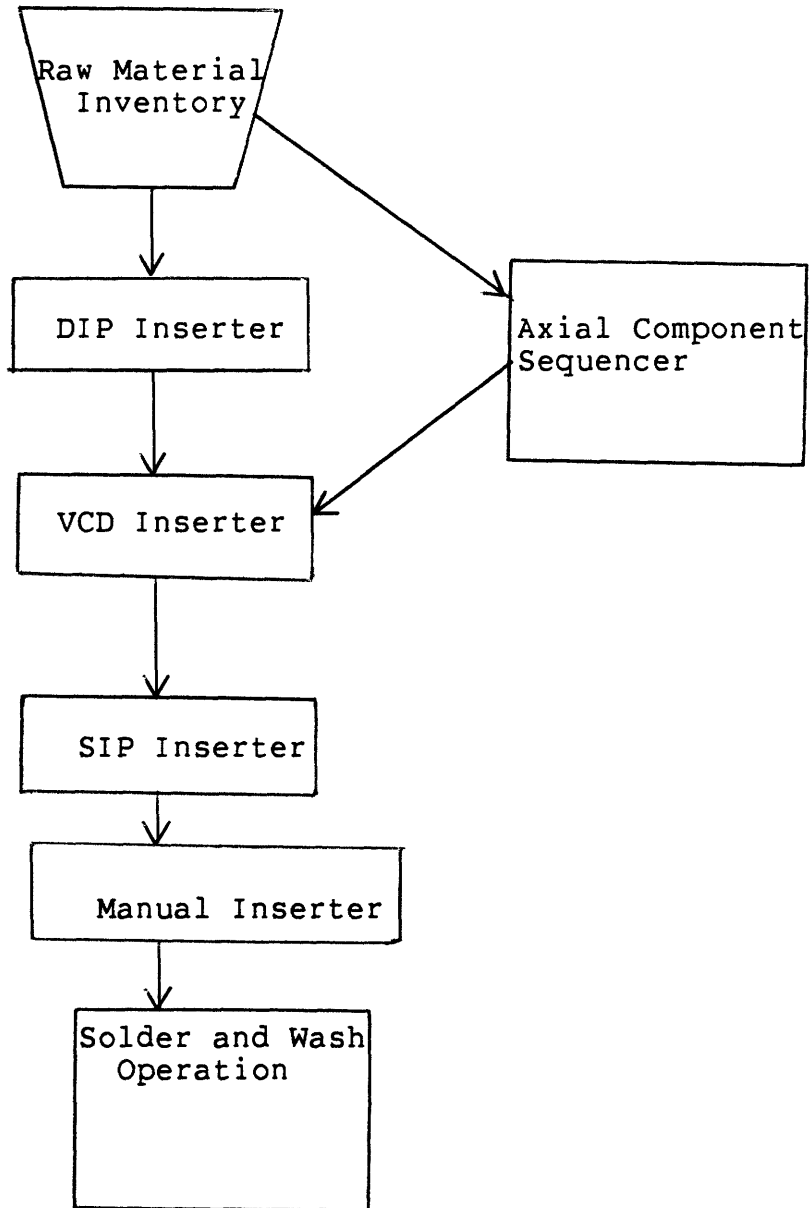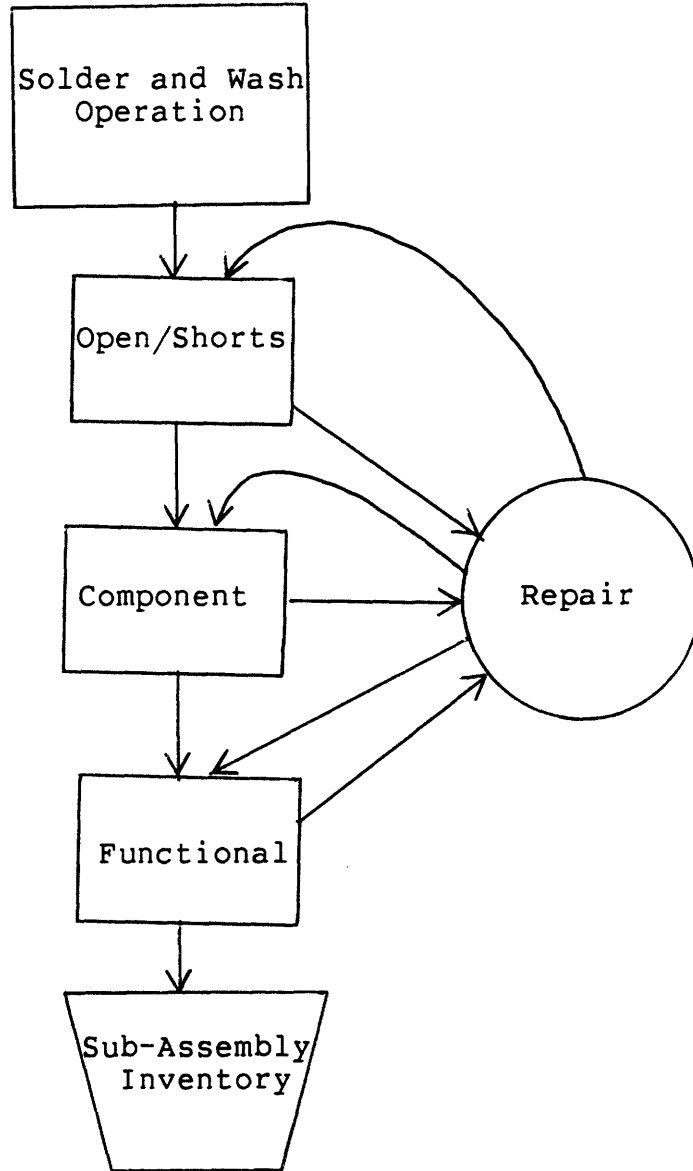
Final Test and Repair Operation:
Diagram of Electronic Tests Performed

```
          ┌──────────────────┐
          │ Solder and Wash  │
          │   Operation      │
          └──────────────────┘
                   │
                   ▼
          ┌──────────────────┐
          │ Open/Shorts      │ ──────┐
          └──────────────────┘       │
                   │                  │
                   ▼                  ▼
          ┌──────────────────┐    ┌────────┐
          │ Component        │ ──▶│ Repair │
          └──────────────────┘    └────────┘
                   │
                   ▼
          ┌──────────────────┐
          │ Functional       │
          └──────────────────┘
                   │
                   ▼
          ╱──────────────────╲
          │ Sub-Assembly     │
          │   Inventory      │
          ╲──────────────────╱
```

Chapter 3: Mathematical Model

In this chapter I will construct a mathematical model
that will somewhat explain the the process time required to
manufacture a batch of PCB's.

3.1 COMPONENT INSERTION OPERATION

In brief, the assembly operation consists of inserting
electronic and hardware components, and soldering or
affixing, them in place at a predetermined location on the
PCB. The choices to do this are as follows:

1. automatically insert and solder the component in
place;

2. manually insert and automatically solder the
component in place;

3. manually insert and solder the component in
place.

Table Three contains the variable process times necessary
to insert and solder DIP components, axial components, and
hardware components.

Exhibit Five reveals an equation that can be used to
describe the total time it requires to assemble a PCB.
Please note that set-up times are not included in either
Table Three, or Exhibit Five. By using a typical PCB, it
can be shown that the time to assemble a PCB varies with
the percentage of components that are auto-insertable.

Table Four details this relationship.

3.2 INTERACTION BETWEEN ASSEMBLY AND TEST

The main interaction between assembly and test is a figure of performance: Defects Per Unit (DPU). This figure is the number of defects scored at final test divided by the number of PCB's tested.

The frequency distribution of DPU's approximates a poisson distribution. It then follows that the percentage of PCBs with zero defects is equal to the natural number (e) to the negative DPU (see Table Five).

3.3 FINAL TEST AND REPAIR OPERATION

Five parameters determine the total time to test a PCB. These parameters are as follows:

1. first pass yield
2. time to test a fault-less PCB
3. time to correct a fault
4. time to set-up the operation
5. time to find a fault

Equally as important as minimizing the time it takes to test a PCB, is that the PCB will perform as the design engineer intended.

If the first pass yield approaches 100 percent, the time to test a PCB will converge to a value slightly more than the time to test a fault-less PCB (see Exhibit Six).

Before I discuss the mathematical model of the final test and repair operation, I will define the terms being used. The first pass yield is the fraction of PCBs that meet the final test specifications the first time tested. The time to test a fault-less PCB encompasses all three types of electronic test: electrical open/short, component, and functional. The time to correct a fault is the amount of time it requires or correct a fault once it is found. The time to set-up the operation is the time it takes the test operator to set-up the tester. The time to find a fault is the time it takes the repair technician to hunt around and locate the fault.

The time to test a fault-less PCB is a combination of the function and complexity of the PCB, and the speed and sophistication of the automatic test equipment (ATE). For example, a large ALU (Arithmetic Logic Unit) PCB, which usually has at least two hundred ICs, would require a more comprehensive, and thus a longer test, than a 3 by 5 inch Disk Drive Controller, which may have twenty-five components. Thus, the ALU would take considerably longer to test than the Disk Drive Controller. For the purposes of the following discussion, I will use a typical time to test a fault-less PCB in my analysis.

To analyze the Final Test and Repair Operation, I have constructed a mathematical model (see Exhibit Six). This model does not fully capture the stochastic behavior present in the Final Test and Repair Operation. Nevertheless, the insight gained should outweigh the loss of predictive capability of this model. Table Six compares the test and repair labor required for two different final test and repair operations.

For example, let us suppose that a Final Test and Repair Operation has the following set of characteristics:

    1. first pass yield - 0.607

(quality level = 0.5 DPU)

    2. time to test a fault-less PCB - 5 minutes;

    3. time to correct a fault - 5 minutes;

    4. time to set-up the operation - 12.5 minutes;

    5. time to find a fault - 60 minutes;

By inspection of Table Six, the PCB should require 34.1 minutes of direct labor time to test and repair.

On the other hand, if the quality level of the PCBs that are emerging from the assembly process were to increase, or in other words the defect level were to decrease, the time to test and repair a PCB should decrease. In specific, if the defect rate decreased from 0.5 to 0.1 DPU, the time to test and repair a PCB should decrease from 34.1 minutes to 13.7 minutes (60 percent

decrease).

Ideally, if the quality level was raised to 0.025 DPU, the time to find a fault decreased to 30 minutes, the time to test a fault-less PCB decreased to one minute, and the time to set-up the ATE decreased to 7.5 minutes - the total time to test and repair a PCB should decrease to 3.3 minutes (91 percent decrease) (see Table Six - Case B).

So far, none of the previous calculations have been adjusted for the initial automatic tester programming time, which is 400 to 600 hours. The initial programming time will be amortized over the total number of PCBs manufactured. For instance, if it requires 500 hours to initially program the machine to automatically test a PCB, and 5,000 PCBs are ultimately manufactured, the start-up labor for each PCB would be 0.1 hours. However, if only fifty PCBs were ultimately manufactured, each PCB would incur a start-up labor charge of ten hours, which would be greater than the time to test and repair a PCB by at least a factor of ten.

In summary, the quality level of PCB's emerging from the assembly operation will determine the production rate of the PCB A & T Operation, for a certain amount of resources. Thus, the quality level will determine the capacity derived from a certain amount of resources.

Table Three

Assembly Times
(Seconds)

Task	DIP Component	Axial Component	Hardware Component
Automatic Insertion	1.08	1.08	3
Manual (Hand) Insertion	3.00	3.00	45
Automatic Soldering	25 seconds per PCB		--
Manual (Hand) Soldering	40	10	--

Note: DIP Component that is being inserted and soldered is of the eight pin class

Exhibit Five

Component Insertion Equation
(Seconds)

$\# = E + H$

$E = X + Y$

$S = 25 + 40(R*Y) + 10(R*X)$

$T = 1.08*P*E + 3(1-P)E + 45*H + S$

Where:

T = time to insert and solder components onto the PCB

$\#$ = total number of components on PCB

X = number of axial components

Y = number of DIP components on the PCB

H = number of hardware components of PCB

P = fraction of electronic components on PCB
that are auto-insertable

R = fraction of electronic components that are
automatically soldered

S = time to solder components

For a Typical PCB: $\# = 205$
$X = 60$
$Y = 140$
$H = 5$
$R = .01$

Table Four

Variable Process Times to Insert and Solder Components

(Minutes)

Percent of electronic components that are auto-insertable	Variable assembly time
100	8.8
90	9.4
80	10.1
60	11.4
50	12.0
40	12.7
20	13.9
0	15.2

Note: 1. See note 1 below Table One.

2. Hardware components are manually inserted.

3. Same percentage of DIP components as axial components are inserted.

4. percentage of electronic components that are not automatically soldered is 1 percent (R=0.01).

Table Five

Relationship Between Assembly and Final Test

Defects Per Unit (DPU)	First Pass Yield at Final Test Operation
2.0	.135
1.5	.223
1.0	.368
0.5	.607
0.4	.670
0.3	.741
0.2	.819
0.1	.905
0.05	.951
0.025	.975
0.0025	.990

Mathematical Representation of
Time to Test and Repair a PCB

$$p = e^{-DPU}$$

$$R = t_f + t_c * DPU + t_v + t_s/(10(1-p))$$

$$T = t_v + t_s/10 + (1 - p)R$$

Where:

t_v =   time to test a fault-less PCB

p =   first pass yield at final test

DPU   =   Defects Per Unit

R =   time to Repair a PCB

t_f =   time to locate a fault

t_c =   time to correct a fault

t_s =   time to set-up the operation

Assumptions:

1. All faults require same amount of time to locate.

2. All faults require same amount of time to repair.

3. The PCB will be re-tested fault-free, if repaired.

4. The frequency distribution of DPU's is poisson.

Table Six

Effect of PCB Quality of
on Final Test and Repair

Quality Level (Defects Per Unit)	Case A	Case B	Diff. (A-B)	Normal Diff. (Base=16.2)
2.0	72.3	38.0	34.3	211.7
1.5	63.8	32.4	31.4	193.8
1.0	51.7	25.3	26.4	162.0
0.9	48.7	23.6	25.1	154.9
0.8	45.5	21.8	23.7	146.3
0.7	41.9	19.9	22.0	135.8
0.6	38.2	17.8	20.4	125.9
0.5	34.1	15.7	18.4	113.6
0.4	29.6	13.4	16.2	100.0
0.3	24.7	10.9	13.8	85.2
0.2	19.5	8.3	11.2	68.5
0.1	13.7	5.5	8.2	50.6
0.025	9.0	3.3	5.7	35.2

Note: Case A- t_f=60 min.
t_s=12.5 min.
t_v=5 min.

Case B- t_f=30 min.
t_s=7.5 min.
t_v=1 min.

Chapter 4: Issues

In this chapter I discuss issues that are important to the normative and descriptive operation comparison.

4.1 RAW MATERIALS SHORTAGES

For purposes of the following discussion, I will categorize parts shortages as occurring for one of two reasons. First, a parts shortage that occurs due to an addition or change to the Bill of Materials (BOM). Second, a parts shortage that occurs due to any other reason.

Out of the six weeks it requires to assemble and test a PCB, a large portion of the time the PCB is in a queue waiting for parts, or for the necessary productive resource to become available. If a PCB is waiting for parts, the reason for this may be because the part was created by an Engineering Change Order (ECO). If so, the part may be appearing on the Bill of Materials (BOM) for the first time.

The production assembler's, material planner's, and engineer's BOM are almost never in agreement (see Exhibit Seven). When a product is first introduced, all three BOMs coincide. However, from that point on, the three BOMs tend to diverge in content from one another. If the product reaches a mature stage, the three BOMs may once again converge; however, in the computer system industry,

products tend not to become mature.

A parts shortage occurs when the production assembly BOM diverges from the material planning BOM. The materials BOM is used to run the MRP system, and the production assembly BOM is used to assemble the PCB. Once the parts are not available to assemble the PCB, the batch will reside in a queue waiting for those parts.

A great deal of ECO's are initiated by the manufacturing facility. This is especially true if the PCB's that failed in the field are sent back to the manufacturing facility for evaluation and repair. After the manufacturing facility initiates the ECO, a long approval process follows. The long approval process results in change made to the Engineering data base, and subsequently to the materials BOM. Finally, the change to the materials BOM is transmitted to the plants who initiated the ECO. From start to finish, this process can take up to six weeks. In the meantime, the materials planners are not supplying the proper parts, and parts shortages may result.

Approximately 1/4 to 1/3 of all batches released to the production floor are short the required raw material, in the company that is under study. The batches reside in a queue and wait for the parts to arrive. Once the parts arrive, these batches are expedited to meet the original production schedule, which causes an even greater

disruption to the manufacturing facility.

Simply stated, any project that is aimed at reducing the time a batch resides in a queue must ensure that complete batches are released to the production floor.

On the one hand, if the missing part is carried in stock, a larger safety stock can reduce the exposure to this problem. On the other hand, if an ECO creates a new part or substitutes a new part for an old part, the batches being released incomplete will have to wait until the part is ordered, and received. No amount of safety stock of existing parts will help to reduce the problems created by an ECO which requires a new part.

4.2 ENGINEERING CHANGE ORDERS (ECO'S)

With every ECO comes the possibility that a large portion of WIP and sub-assembly inventory must be re-worked or scrapped. The purpose of these actions are to embody the latest engineering change into as much product as possible. One of the main reasons for scrapping a PCB is that the wiring layout for the PCB has changed so much that it is neither technically nor economically feasible to assimilate the change with jumper wires.

If the PCB's affected by the ECO are re-worked or scrapped, a disruption will occur on the production floor. First, if the PCB's affected by the ECO are re-worked, productive resources - usually direct labor - will be deployed to perform the necessary re-work. Second, if the PCB's affected by the ECO are scrapped, a new batch of PCB's will have to be released to the production floor, and expedited to meet the production schedule. In both of the above cases, an avoidable task captured limited resource.

The smaller the levels of WIP and sub-assembly inventory, the less risk there is that an ECO will cause a disruption to the PCB A & T Operation. As was discussed before, the only way to reduce levels of WIP inventory is to increase capacity, or to improve production scheduling.

4.3 MANUFACTURING CONTROL SYSTEM

The normative operation must have a comprehensive manufacturing control system to be successful.

In an average production day, approximately seventy batches of PCB's will be released to the production floor, at the company under study. After being released to the floor, there are at least twenty possible queues that the batch can visit. Assuming no capacity constraints, an ideal detailed scheduling system will force the ratio of process time to manufacturing cycle time to approach one.

For a manufacturing cycle time of six weeks, or thirty production days, there are at least 42,000 queue/batch order cells (42,000=30*70*20) in the queue/batch matrix active on the production floor at any one time. Tracking each individual batch through the assembly and test operation is not trivial task. Furthermore, scheduling these batches so that the work is balanced between and within the work centers and that no bottlenecks occur is even a larger task.

The foreman on the shop floor, unless otherwise instructed by the production scheduler, will load his work center in the most efficient way. Sometimes, the foreman will load his work center in the most efficient manner for not only his work center but the work centers down stream from his own. When the WIP inventory levels are drastically reduced, the foreman will not have an extensive portfolio of batches to choose from. The work centers will be more tightly coupled to one another, and the detailed decision rules to schedule the production will have to be more sophisticated.

4.4 Ways to Increase Capacity

To reduce the manufacturing cycle time of the PCB assembly and test operation, the the capacity of the operation should be expanded. To accomplish this expansion, at least four ways exist. These ways are as follows:

1. reduce process time of operation;

2. reduce quality defects;

3. balance work between operations;

4. improve scheduling methods.

As the ratio between the variable process time and the manufacturing cycle time approaches one, the work will flow in a more continuous manner. Once an ideal continuous flow is attained, the detailed scheduling system will have zero slack.

4.4.1 Reduce Process Time. There are two ways to reduce the process time of an operation. First, the fixed process time (i.e. set-up time) can be reduced. Second, the variable process time can be reduced.

As the time to set-up an operation for a batch decreases, the capacity of the operation will increase. There are many ways to reduce the set-up time of an operation. For example, if there was a universal grid system for PCB layout design, the automatic tester could be

fixture-less. This would mean that the ATE operator would
not have to install a fixture on the machine for every
different type of PCB tested. As a result, the set-up time
would decrease.

4.4.2 Reduce Quality Defects. As the need for PCB repair
decreases, less work will be done on each PCB; thus, the
capacity of the entire operation will increase. As a
result of the increase in capacity, PCB's will not queue up
in and before the Final Test and Repair operation.
Consequently, the manufacturing cycle time will be reduced.

If the raw materials are of higher quality and are
designed to be more easily inserted, soldered, and tested,
the PCB will be assembled and tested more quickly. Less
repair work will have to be performed on the PCB.
Likewise, if the assembly operation introduced less defects
- by better machines or better trained, more careful
production workers - less repair work would have to be
performed on the PCB.

In the final analysis, the quality of a batch of PCB's
that are emerging from the assembly operation will largely
determine the time it requires to test and repair batch of
those PCB's. The time to test and repair a PCB is now
approximately five hundred percent more than it should take
to test a defect-free PCB. Also, it requires twice as long
to test and repair PCB's as it does to assemble PCB's.

To raise the quality of the PCB that emerges from the assembly operation, the production workers could self-inspect the PCB's as part of the assembly routine. In turn, defects would be found, and corrected sooner. Usually, less time and effort is required to prevent a defect than is required to repair a defect.

There are many illustrations of production worker self-inspection. I will describe one so that the reader can understand what I am writing of. After most of the components are inserted, the PCB is soldered and washed. Automatic soldering of PCB's is an art.

The number of defects introduced by the automatic soldering process depends on many factors such as the orientation of the PCB as it travels over the wave of solder, the temperature of the pre-heaters, and the solder, the speed at which the PCB is conveyed over the heater and the wave of solder, and the specific gravity of the solder-flux. Depending on the geometry, component type, and component density of the PCB, the wave-solder machine operator must adjust the above mentioned factors to fit the situation.

An operator who is good at this analysis, can be better by a factor of ten to a new operator, and by a factor of 1.5 to an operator who is mediocre at this analysis. The end result is that more or less solder defects will be introduced depending on the knowledge and

skill of the wave-solder operator. Consequently, most of these defects will have to be corrected at the next work center, which is the Final Test and Repair Work Center.

A good wave-solder operator carefully monitors the wave-solder process. If the performance of the wave-solder process decreases, corrective action is quickly applied by the operator. This quick and accurate reaction by the operator will save money downstream of the wave-solder machine.

Not only can defects be prevented by careful and wise assembly techniques, but they can also be prevented by the type of machine being used to assemble the PCB's. For instance, back to the automatic soldering example. Different automatic soldering technologies and machines provide different rates and types of solder defects. By purchasing the proper machine, and maintaining it properly - solder defects can be drastically reduced. A similar argument can be made for other machines used in the PCB Assembly and Test Operation.

4.4.3 Balance of Work Between Operations. If all
operation's process times were similar in value, the
assembly and test process would become more balanced; and
in turn, the capacity of the assembly and test operation
will increase. To balance the PCB A & T operation, work
should be transferred from the operations that are
over-utilized to those that are under-utilized.

4.5 ELECTRONIC TESTING STRATEGY

There are two ends to the testing strategy spectrum.
On the one end of the spectrum, cheap, low quality raw
material is purchased and assembled; once this is done,
the PCB can be tested and repaired until it performs as the
design engineer intended it to perform. On the other end
of the spectrum, expensive, high quality raw material is
purchased, carefully assembled, and shipped out without a
final test. The former strategy requires fast and
sophisticated automatic test equipment (ATE), the latter
strategy requires no test equipment. Now, of course,
neither strategy is practiced as stated; however, this
contrast will be useful for the discussion that follows.

Defects can be classified into one of two categories.
The categories are as follows:

1. supplier-related defects

2. assembly-related defects

The first type of defect is where the electronic components are defective when they arrive from the supplier. The second type of defect happens when the components are inserted into the PCB, and soldered in place. Assembly-related defects such as the following frequently occur: solder-bridges, bent component leads, warped PCBs, static discharge that causes semiconductor devices to fail, solder-defects (other than solder-bridges), excessive heat at solder-wave that causes components to fail, over-crimped leads, and mis-inserted components.

If both types of defects - supplier-related and assembly-related - could be reduced to a very small number, the need for the final test and repair operation would either be reduced or eliminated. If the components are of high quality, and the assembly operation does not introduce many defects, the need for final test would be eliminated.

For instance, let us say that an assembly operation has a DPU rate of 0.3 defects per PCB. This DPU rate translates into a 74.1 percent chance that a PCB will have zero defects (see Table Five). However, when a Central Processing Unit (CPU), which contains five PCB's, is configured together for the first time, the probability that the CPU will work is 22.3 percent ($0.223=0.741^5$). Yet, if the defect rate was lowered to 0.025 defects per PCB, the percent chance that the CPU will work the first

time is 88.1 percent ($0.881=0.975^5$).

In the first instance, where 87.7 percent of all CPU's were in need of repair, it would not be cost-effective to troubleshoot the whole CPU. The number and complexity of the problems will be too many for a technician to repair within a reasonable time. In the second instance, it may be cost effective to test the PCB's when they are aggregated, foregoing testing them individually.

4.6 INTRODUCTION OF NEW PRODUCTS

If the automatic test programmer could access the engineering design data base, and manipulate that data base in a powerful manner, the initial programming time may be drastically reduced. As of today, no such method exists where the Test Equipment programmer can access and manipulate the engineering data base.

4.7 CHANGE TO EXISTING PRODUCTS

When an ECO is to be incorporated into the existing product design, two tasks are the most difficult to alter. These two tasks are automatic electronic test and automatic component insertion. In both cases, the machines need to be re-programmed.

Exhibit Seven

Diagram of the Flow of ECO Information
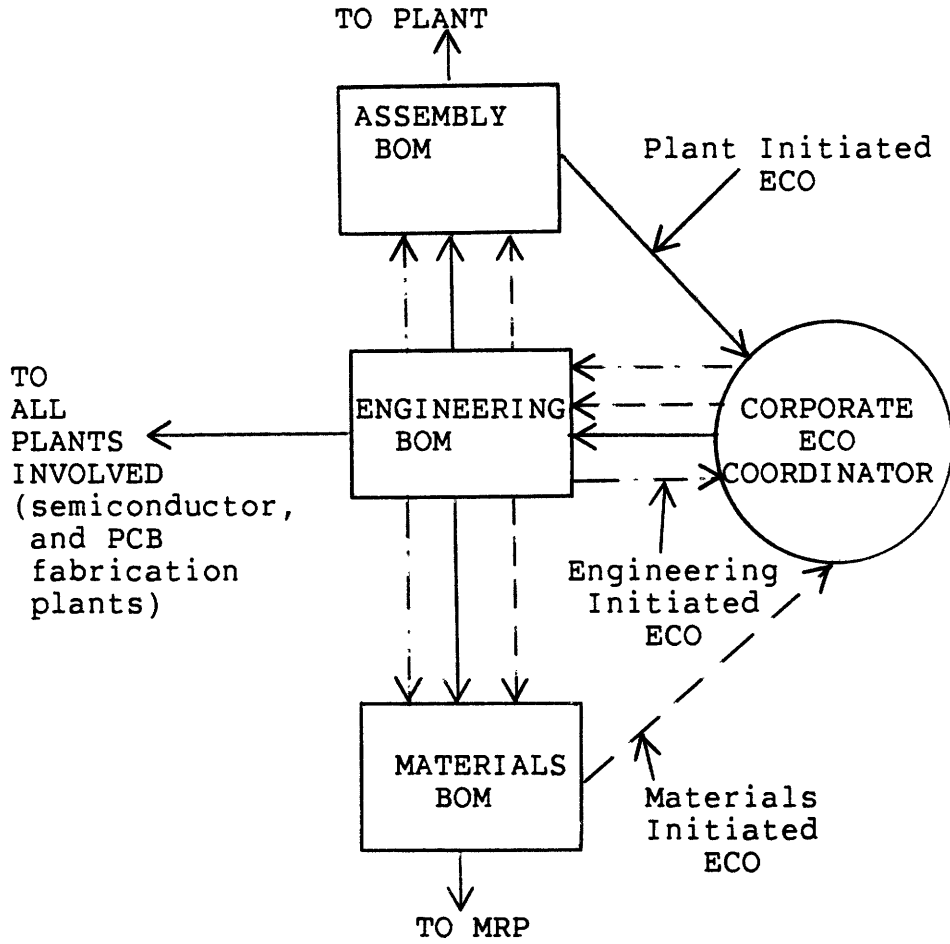
Chapter 5: Normative Operation

The following description of the normative operation evolved partially from the field study at a computer system manufacturer, and partially from my work experience as a test equipment, industrial and process engineer in the computer system industry.

The major difference between the descriptive and normative operation is the approach taken to both assembling and testing a printed circuit board. The following changes to the descriptive operation represent the normative operation. These changes are as follows:

1. increasing the capacity of the component insertion operation;

2. increasing the capacity of the final test and repair operation;

3. balancing the work flow between the component insertion and final test and repair operations.

To increase the capacity of the component insertion operation:

- DIP components, should be dedicated to the channels of the automatic inserter machines;

- a higher percentage of auto-insertable components should be used.

To increase the capacity of the final test and
repair operation:

- a new high speed automatic tester should be
installed;

- the quality of the PCB's emerging from the
assembly operation should be increased.

However, these two actions are counter to one another. As
the quality of PCB's that emerge from the assembly
operation increases, the need for a high-speed automatic
tester decreases.

To balance the work flow between the component
insertion and final test and repair operation:

- the middle electronic final test, the components
test, should be pushed upstream.

The electronic test that compares the component's
performance versus it's design specifications can be pushed
upstream by two methods. First, higher quality parts can
be purchased, or more incoming inspection can be performed.
Second, an in-line test can be performed at the time when
the component is being inserted into the PCB.

To improve the quality of PCB's emerging from the assembly operation:

- higher quality raw material should be used;

- rudimentary components tests should be done at at the time just before the component is inserted into the PCB;

- better care should be exercised in assembling the PCB's.

5.1 COMPONENT INSERTION OPERATION

The capacity of the component insertion operation can be increased by reducing the fixed process time, or by reducing the variable. process time of the component insertion operation.

The capital expense for the automatic inserters will be approximately twice as high as the descriptive system, more automatic inserters are needed for the same amount of production.

5.1.1 Reduce Fixed Process Time. There are two parts to the set-up procedure:

- load the machine with raw material;

- load the insertion instructions into the machine;

- align the insertion head for first insertion.

First, the operator need not load raw material into the machine for each batch of PCB's. The difference between the descriptive and the normative operation is that the operator need only keep the machines stocked with raw material. Whereas, in the descriptive operation, the operator had to carefully load the automatic inserter with a unique set of components. This led to mistakes such as components being placed in the wrong automatic inserter channels, and thus being inserted at the wrong locations on the PCB. With the normative operation, mis-inserted components should become a much less frequent occurrence.

Second, the automatic inserter is, and will be controlled by a computer. The difference between the descriptive and the normative operation is that the computer will sense what type of PCB the batch is composed of, and load the insertion instructions from a central data base. This will eliminate the need for an operator to load the instructions, and thus save time.

Finally, the insertion head will be aligned by an optical sensing device. The difference between the descriptive and the normative operation is that the insertion head will be automatically aligned under the control of computer. This will eliminate the need for an operator to manually align the insertion head over the the first insertion site.

In total, a decrease of 50.5 percent in total fixed process time (i.e. set-up time) will result from the above three changes (see Table Seven). This decrease of set-up time will result in a 5.5 percent increase of capacity in the assembly operation.

To increase the capacity of the Component Insertion Operation, the fixed or variable process time can be reduced. Previously, methods to reduce the fixed process time were discussed, now I will discuss ways to reduce the variable process time.

5.1.2 Reduce Variable Process Time. Simply put, if a greater percentage of the components - electronic and hardware - can be successfully inserted into the PCB by automatic means, the variable process time will decrease.

The task of inserting piece part components into the holes of the printed circuit board is divided among two methods: automatic and manual insertion. Out of these two methods, it is most economical to insert the component by automatic means. Yet, only 80 percent of the piece part components are inserted by machine.

The task of inserting components into the holes of a PCB starts at the design stage. Depending on the design, the layout of the wiring diagram, and more importantly, the choice of electrical components and hardware, more or less of a percentage of the total piece parts will be easily

insertable by machine.

If the percentage of components that are inserted by automatic means rose from eighty to ninety percent, the variable process time of the assembly operation would decrease from 10.1 to 9.4 minutes per PCB. The capacity of the assembly operation would increase by 13.0 percent.

If both the fixed and variable process times are reduced, the capacity of the assembly operation will increase by thirty-six percent.

5.1.3 Balance the Work Flow. If any of the three levels of final test can be distributed upstream of final test, many benefits would emerge. First, the time to test a PCB will be drastically reduced. Second, a better balance between work centers will be struck, since the final test work center has the least capacity of all the work centers. Third, an individual PCB will visit, and remain less queues, since it will most likely avoid the morass of queues awaiting it in the Final Test and Repair Work Center. In sum, the manufacturing cycle time would be drastically reduced.

5.2 FINAL TEST AND REPAIR OPERATION

The capacity of the final test and repair operation can be increased by reducing the process time; which will in turn reduce the waiting time. Another way to increase capacity, however, is to reduce the number of defects that are emerging from the assembly operation.

5.2.1 Reduce Fixed Process Time.

By storing the testing routines in permanent memory within the tester, the tester could be set-up more quickly.

5.2.2 Reduce Variable Process Time.

The new tester is many times faster than the tester used in the descriptive operation. In turn, the PCB can be stepped through a test procedure much more quickly.

5.4 DETAILED PRODUCTION SCHEDULING

By dedicating DIP components to automatic inserter machines, it is possible that the PCB will visit more than one machine. In turn, queues will develop before each machine.

A situation exists which makes it more likely that a batch will visit more than one machine, in addition to the DIPs being dedicated to particular machines. This situation is called "footprinting."

A "footprint" is the name given to the shadow that the automatic insertion head makes on the surface of the PCB. On the one hand, to positively constrain the DIP, the insertion head must be approximately as large as the component it is inserting. If the insertion head is smaller than the component, the DIP may not be placed precisely on target. As a result, some or all of the pins may become bent, and these pins will not make the necessary positive electrical contact.

On the other hand, if the insertion head is larger than the component being inserted, the insertion head will overhang off the edges of the top part of the DIP. When the DIP is inserted, the exposed portion of the tool may crush a component which is adjacent to the insertion site. The crushing of a component adjacent to the insertion site on a PCB is called "footprinting." Needless to say, "footprinting" should be avoided. In sum, the insertion head should be matched in size to the component that is being inserted.

By assigning a DIP component to a DIP inserter, the chances are increased that a single PCB will visit more than one automatic inserter. This is because the PCB's usually have more than one size of DIP component. In the present operation, one DIP inserter can insert all DIP's onto a PCB. Whereas, due to the situation called "footprinting", a PCB will most likely visit more than one

DIP inserter before the PCB is assembled.

Once the assignment of DIP components to machine is made, the work flow between the the bank of machines must be balanced. The balance between the machines should be robust. Also, Once the DIP/machine relationship is determined, the PCB must visit a certain number of machines to be complete.

In the normative operation, a dynamic scheduling program will be needed to dictate the production schedule for the automatic inserters. If the configuration of inserters are not properly scheduled, a queue overflow and a production bottleneck may occur.

A dynamic scheduling program will be able to route the batches through the arrangement of automatic inserters. Due to the match between the size of the insertion head, and the size of the DIP component - it does not matter which sequence the batch visits the needed inserters. This allows for scheduling flexibility.

A PCB that has to visit N machines, can do so in N! ways. Yet after each successive visit, (N-1)! ways still exist. Until only one way exists (1!=1), then the PCB will visit the last machine. The flexibility as to which machine the PCB will visit narrows as the PCB is loaded with components, until only one choice remains. Intuitively, if the bundle of jobs in the inserter work center can include an even mix of jobs that have three or

more handlers to visit, two handlers to visit, and only one handler to visit, the alternatives available to the scheduling program will be many. However, once the bundle of jobs in the DIP inserter work center have a high percentage of jobs that have to visit only one machine before they are complete, the scheduling problem becomes more difficult.

The normative model does not allow for a machine to breakdown, nor for a kit to be released incomplete. Consequently, the scheduling system must realize which machines are operative.

Clearly, the detailed scheduling necessary is many times more complex in the normative operation as compared to the descriptive operation.

5.5 Manufacturing Control System

When the work in process inventories are reduced by as much as 80 percent the job definitions and manufacturing procedures will change. As a result, management and labor will have to re-learn their jobs.

An example of a trend that is occurring due to automation is the change in the method of overhead allocation. A typical planning and control system uses direct labor hours to allocate overhead. However, as the labor base is decreasing with respect to the capital base, it makes less sense to use direct labor hours as a basis to

allocate overhead costs.

When the manufacturing cycle time is reduced from six weeks to a much smaller amount of time, management techniques that have been built over a lifetime may not work when the manufacturing cycle time and WIP inventory are drastically reduced. As a result of the shorter cycle time, the amount of slack available in the production scheduling decision has been reduced; thus, a more sophisticated detailed scheduling system must be used.

The underlying assumptions of management technique are embedded into the regular routine of the manufacturing facility. To allow for these assumptions to be brought out and discussed, managers may have to be retrained.

To accomplish to task of tracking each batch of PCB's, a relational data base can be set up. As the reader may know, a relational data base is structured by ordering the information in tables or matrix form. The types of relationships that should be included in this data base is as follows:

1. queue/batch;

2. DIP type/automatic inserter channel number;

3. PCB type/batch;

4. raw material/PCB type;

For simplicity, the Manufacturing Control System (MCS) for the normative model was designed to be as independent as possible from the material requirements planning (MRP) system.

5.6 ALTERNATIVE WAY OF INCREASING CAPACITY

An alternative to reducing the set-up time is to increase the capacity of the component insertion work center by adding more inserters. The possible justification of such a project would be the reduction in inventory investment. I will compare this alternative to the normative operation.

In short, the main differences between the two approaches would be as follows:

- labor requirements,
- capital requirements,
- fixed process time of component insertion operation,
- the complexity of the detailed production scheduling system.

The normative and alternative operation both add to the capital base. In fact, the normative operation will require twice as large a capital outlay as the alternative operation. While the normative operation reduces the labor base, the alternative operation adds to the labor base.

The normative operation will need half the time that the alternative operation needs in terms of fixed process time (set-up time).

The drawback to the normative operation, besides the risk of a business down turn increasing the capital charge for a unit of product, is the increased complexity of the detailed decision rules necessary to schedule production.

An advantage to the normative operation is the ability to maintain similar labor requirements for a wide range of production rates. In the normative operation, a few personnel tend many inserters. In the descriptive and alternative operation, every inserter needs an operator; for every inserter that is put into production, a person will be needed to tend that inserter. Whereas in the normative operation, the production rate is adjusted by releasing more or less batches to the bank of machines. In sum, the labor requirements for the normative operation are much more stable over wide variations of the production rate. This stability simplifies the problem of balancing labor between work centers.

Table Seven

Direct Labor Times for
Normative Assembly and Test Operation
(Minutes)

Operation	Set-Up	Variable	Total
A. Component Insertion	26	85	111
B. Solder and Wash	10	8	18
C. Final Test and Repair	7.5	60	67.5
Totals	43.5	153	196.5

Note: 1. See Notes 1 and 2 below Table One.

2. Assembly Time = 129 minutes.

Table Eight

Direct Labor Times for
Normative Component Insertion Operation
(Minutes)

Work Center	Set-Up	Variable	Total
DIP Inserter	13.5	45	58.5
VCD Inserter	7.5	30	37.5
Manual Inserter	5	10	15
Totals	26.0	85	111

Chapter 6: Advantages, Disadvantages and Transition

In brief, the advantages - or benefits - of the normative operation when compared to the descriptive operation are as follows:

1. lower investment in WIP inventory;

2. reduction in labor costs;

3. less ambiguity in manufacturing operation;

4. reduction in customer order cycle time;

5. fewer costs generated by ECO's.

Conversely, the disadvantages - or costs - of the normative operation when compared to the descriptive operation are as follows:

1. large capital expenditure;

2. more tightly coupled work centers;

3. more difficulty in scheduling production;

4. necessity to acquire new work skills;

5. more difficulty in introducing new products;

6. more difficulty in changing existing product designs.

In this chapter I will first discuss the advantages; then I will discuss the disadvantages.

6.1 ADVANTAGES OF NORMATIVE OPERATION

Many advantages are derived from the reduction in manufacturing cycle time. A reduction in manufacturing cycle time can cause a reduction in inventory in two ways. First, the WIP inventory is less due to a lower manufacturing cycle time. Second, the safety stocks that are held to compensate for demand forecast error are reduced. In addition, all other benefits as stated above do follow from a reduction in manufacturing cycle time, except for a reduction in labor costs. The reduction in labor costs follow from a reduction in defects and a reduced labor requirement for component insertion.

6.1.1 Lower Investment in WIP Inventory.
When the manufacturing cycle time is lowered by one production day, the work-in-process inventory is reduced by approximately three percent, if the initial manufacturing cycle time is thirty production days (six weeks). Specifically, if the normative operation does reduce the time to assemble and test PCB's from six weeks to one week, a eighty-six percent reduction in WIP inventory should result.

There are two views on how to treat the monetary benefits of WIP inventory reduction. First, a non-recurring benefit can be taken equal to the reduction in WIP inventory levels. Second, a stream of savings can be discounted to the present, and then these discounted savings can be summed over time. The discount rate is the weighted average cost of capital.

No matter which method is used, the savings will be the same results. The savings will be equal to the the reduction in the value WIP inventory. Furthermore, it does not matter whether the savings are considered before or after federal income taxes since the two methods still yield the same.

There are two ways to fund an increased requirement for working capital. First, the firm can use internally generated cash to fund the working capital requirement. Second, the firm can access the capital markets by issuing instruments of ownership or liability to fund the working capital requirement. Either way, interest income is foregone, or undue interest expense is paid. If the amount of inventory per dollar of sales revenue can be decreased, the working capital requirements per sales dollar will follow. In turn, a substantial savings can be had by a computer systems manufacturer.

6.1.1.1 Calculation of WIP Inventory. The WIP inventory level is a function of the production rate and the manufacturing cycle time. The production system can be thought of as a pipeline, with raw materials inventory at one end, and sub-assembly inventory at the other end of the pipeline. WIP inventory is in the pipeline. To estimate WIP inventory, the manufacturing cycle time is multiplied by the production rate. The product of this calculation is divided by two, to account for the differing degrees of completion of the product in the pipeline. The end result of these two calculations is an estimate of the value of the product in the pipeline, that is, the work in process inventory.

A plant that is building five thousand production PCBs per week, will have a weekly production rate of 1.75 million dollars per week (average cost of a PCB is $350). If the manufacturing cycle time is six weeks, then the WIP inventory will be 10.5 million dollars. If the manufacturing cycle time can be reduced to one week, the WIP inventory will decrease to 1.75 million dollars. In sum, the reduction in WIP inventory, and savings to the company, will be 8.75 million dollars - a substantial savings, indeed.

6.1.2 Reduction in Labor Costs. The normative operation
should not only reduce the amount of direct labor, but it
should also reduce the number of foremen.

Savings in direct labor should occur in both the
component insertion and final test and repair operations.
To illustrate this point I will contrast the present and
normative operation's labor requirements. This analysis is
not meant to be a comprehensive list of the impact of the
change from the present to the normative operation.
Rather, I mean to transmit to the reader a sense of where
labor savings may be had.

The present operation requires a person at each
automatic DIP inserter, whereas the normative operation may
only require one person for every eight automatic DIP
inserters. This one person will monitor the performance of
the eight inserters. As part of this task, this person
will also ensure that there are ample supplies of raw
material loaded in the inserters. An 88 percent reduction
in the number of DIP inserter operators will result from
the normative operation.

Likewise, given the low defect rate level of the PCB's
exiting from the solder and wash operation into the final
test and repair operation, much less test and repair labor
expense will be needed to produce a good PCB.

To illustrate this point, let us calculate what a typical savings in test and repair labor might be. At one point in time, the assembly operation had a 0.5 defects per unit. Given this level of quality, 34.1 minutes (Case A - Table Two) of direct labor time would be necessary to test and repair a PCB. Now, if the quality level improved to 0.025 DPU, it would only require 9.0 minutes of direct labor time to test and repair a PCB. The 74 percent reduction in direct labor time would result in a corresponding reduction in ATE operators and repair technicians.

In addition, there will be less of a need for production foremen. First, there will be less workers for the foremen to supervise. Second, there will be less for the foremen to do.

The span of control of a production foreman is such that the reduction in production workers could force the merger of one or more work centers. These merged work centers would then be put under the control of one foreman.

In the present operation, the foreman, or work center supervisor, schedules his work center according to his set of of rules. The individual work centers will have a regimen placed on them that will not allow for much discretion in scheduling. His discretion has been greatly reduced by the concentration of scheduling decisions at the mouth of the production pipeline. Thus, out of the six

work centers, one or more the foreman may not be necessary.

6.1.3 Less Ambiguity in Manufacturing Operation. First the manufacturing cycle time is lowered, then the WIP inventory is reduced. While at the same time, the quality level is raised. As a result, the PCB A & T operation should be easier to troubleshoot.

To illustrate this point, I will compare the present operation with the normative operation. The plant is manufacturing 5000 PCB's per week. The manufacturing cycle time is reduced from six weeks to one week. The defect per unit level is reduced from 0.5 to 0.025 DPU. As a result, the number of defects present in the WIP inventory should decrease from 1500 to 25. Clearly, the normative operation would be easier to troubleshoot should a problem arise.

6.1.4 Reduction in Customer Order Cycle Time. As the reader may know, customer order cycle time is the period between the time a customer orders a product and the time a customer receives the product. In general, when the customer order cycle time is greater than the manufacturing cycle time, more safety stocks are held within the manufacturing operation. In the computer systems industry the customer order cycle time is greater than the manufacturing cycle time. As they become closer in value, the manufacturing operation can lower the levels of safety

stock that are held to compensate for demand forecast error. As a result, cost of operations should be less.

The manufacturing cycle time comprises a significant portion of the customer order cycle time. As the manufacturing cycle time is reduced, the customer order cycle time will also be reduced. With PCB manufacturing cycle times of six weeks, the customer order cycle time is ninety days. If the PCB manufacturing cycle time can be reduced by five weeks, the customer order cycle time should be reduced by a similar amount of time. The improvement in customer service should add value to the computer system.

6.1.5 Fewer Costs Generated by ECO's. As was discussed before, ECO's can be announced at any time. Once they are announced, however, products must conform to the ECO. To do this, great cost may be incurred by re-working or scrapping WIP or sub-assembly inventory. As the manufacturing cycle time is reduced, the exposure to the risk of ECO generated costs should also be reduced.

6.2 DISADVANTAGES OF NORMATIVE OPERATION

I will now discuss the disadvantages to the normative operation when compared to the present operation.

6.2.1 Large Capital Expenditure.

Anytime a large capital expense is incurred, a breakeven point is set. This point represents a production volume level where the incremental fixed costs are equal to the savings to be expected. If the production volume exceeds the breakeven volume, a profit is made on the addition to the capital base. The capacity expansion project under study is no different. If the projected future demand does not materialize, the fixed expense may not be amortized over a large enough production volume to make it profitable. Simply put, the capital charge attached to each PCB will be greater as the production volume is lower. At some point, the incremental capital charge will be greater than the savings made.

6.2.2 More Tightly Coupled Work Centers.

A breakdown in one work center, will cause a ripple effect to occur within the manufacturing facility, since there are no WIP inventories to decouple the work centers. To prevent this from occurring, preventive maintenance of production machinery becomes key. However, this attention to preventive maintenance will add to the factory's overhead.

6.2.3 More Difficulty in Scheduling Production. Before a batch of PCB's are released to the production floor, the effect that the release of this batch will have on the production system will have to be analyzed. This is especially true for the component insertion operation. This type of analysis has not been previously practiced.

As was stated before, there are 42,000 batch/queue cells in the present operation. Any analysis to determine the effect of releasing a batch to the floor was rough at best. The normative operation will have 7,000 batch/queue cells. The decrease in this number will make for a simpler analysis.

The simplicity gained in the reduction of batch/queue cells and the concentration of the production scheduling decision is outweighed by the increase in complexity of scheduling batches through the component insertion operation. As a result of this difficulty to schedule production, other disadvantages follow.

6.2.4 Necessity to Acquire a New Set of Work Skills. Because the work centers are more tightly coupled, and the detailed production scheduling task is more complicated, the normative operation will require a different set of work skills. The managers and workers must either be retrained or relocated.

6.2.5 More Difficulty In Introducing New Products.

When a new product is introduced, the mix of products manufactured changes. It is more difficult to predict what effect a new product mix will have on the capacity of the normative component insertion operation. This change may cause the DIP component/ automatic inserter relationship to be re-evaluated.

The normative operation does not make it any easier to program the automatic inserter or automatic tester.

6.2.6 More Difficulty In Changing Existing Product Designs.

As was stated above, the normative operation has concentrated the production scheduling decision at the mouth of the component insertion operation. With this concentration may come simplicity; however, there is not enough evidence that this is the case. So, any action that causes a change to the component insertion scheme will change the relationship between insertion capacity and production mix.

6.3 Transition

To change from the descriptive operation to the normative operation is a formidable task. Such a change will affect every employee in the manufacturing facility. One of the purposes of the normative operation is to save labor expense. If the sales revenue of the company does

not follow a growth pattern equal to or greater than the labor savings pattern, the company may have to lay-off workers. However, it is doubtful that the quality level of PCB's emerging from the assembly operation will improve to its projected value very quickly. The improvement in quality will most likely occur over time. This will allow the company to pare down the work-force by attrition.

The biggest problem that I see with the normative operation is the computer program that is supposed to accomplish the detailed production scheduling. This computer program is the center of the normative operation. Before this program is written, an operations research study will have to be undertaken. The purpose of this study should be to see which type of decision rules are efficient. Before this is done, I would be hesitant to change the configuration of the automatic inserters.

Chapter 7: Conclusion

After careful analysis of the normative operation, I will now state four main points. These points not only apply to the situation in specific, but also apply to any capacity expansion program in general. These points are as follows:

1. only a partial reduction in manufacturing cycle time will be realized, if the raw materials shortages continue.

2. inventory investment may not decrease if the MRP system is not adjusted for the smaller manufacturing cycle time.

3. capacity expansion projects are interactive in many ways, and therefore these projects need to be combined.

4. production scheduling becomes much different, when the WIP inventory is drastically reduced.

I will now discuss these conclusions in the order listed.

7.1 PARTIAL REDUCTION IN MANUFACTURING CYCLE TIME

If everything goes as planned, only a certain amount of reduction in the manufacturing cycle time will be made by the capital expansion project. A significant portion of the waiting time of the manufacturing cycle time is attributed to raw material not being available when needed. This capacity expansion does not directly address this issue.

The project leaders at the company under study feel that once the normative operation is functioning smoothly, the reasons for a lack of ECO coordination and raw materials shortages will become more apparent. Once these reasons are revealed, efforts can be directed to improving ECO coordination, and reducing the incidence of raw materials shortages. Now, these issues are important, but they can be tolerated. In the normative operation they cannot be tolerated.

Raw material inventory levels can be increased to reduce the instances of shortages, and this action will also reduce the negative impact that ECO's will have. However, one of the intents of the capacity expansion project was to reduce levels of inventory. So, on the one hand, WIP inventory levels are being reduced; on the other hand, to accomplish this reduction, raw material inventory levels may have to be increased.

7.2 INVENTORY INVESTMENT MAY NOT DECREASE

To accomplish a reduction in the work-in-process
inventory levels, raw material inventory levels may have to
be increased. Furthermore, if the MRP system is not
updated to reflect the reduction to the manufacturing cycle
time of the PCB assembly and test operation, inventory
carrying costs will increase - not decrease as intended -
because the WIP inventory saved will be converted into more
expensive sub-assembly inventory.

Before the normative operation can be put in place,
the following question should be asked. What PCB A & T
manufacturing cycle time should be used to drive the MRP
system? The relationship between this value and the the
actual manufacturing cycle time will determine if there is
a savings in inventory investment. And if so, how much
savings will be attained.

7.3 CAPACITY EXPANSION REQUIRES A MULTI-FUNCTIONAL APPROACH

The three separate projects need to be combined. The projects to increase the quality of raw material, to increase the capacity of the assembly operation, and to increase the capacity of the final test and repair operation need to be combined.

The project to increase the capacity of the final test and repair operation is counter to the project to distribute the electronic testing function upstream of the final test and repair operation and the project to purchase expensive, high quality components. If all three projects are successful, the end result will be to have an expensive, highly sophisticated piece of ATE being under utilized.

The key to all three projects is to reduce the defect level of PCB's emerging from the assembly operation. If this can be done, the time to test and repair a PCB, which is now approximately twice the time to assemble a PCB, will be reduced to half the time to assemble a PCB. The bulk of this savings will not result from the final test and repair capacity expansion project. The bulk of this savings will, however, result from the increased level of quality of PCB's emerging from the assembly operation. In sum, efforts to increase the capital base of the final test and repair operation capacity are counter to efforts to increase the quality of PCB's emerging from the assembly

operation.

One possible strategy would be to introduce a high-speed tester when the defect rate was still high. Once the quality of the assembly operation began to improve, the PCB's previously tested by bench methods, or low-speed testers could be tested by the high-speed tester. Until eventually, the high speed tester was testing the bulk of the PCB's being assembled.

7.4 MORE DIFFICULT TO SCHEDULE PRODUCTION

The task of production scheduling will become more difficult for the following two reasons:

1. more difficult to schedule the normative component insertion operation;

2. higher interdependency of work centers on each other, due to the reduction of buffer inventory between them.

First, the normative configuration of automatic inserters will, indeed, result in direct labor savings in the component insertion operation. However, this savings will be made at the cost of a much more complicated detailed production scheduling system. And to a lesser degree, changes to existing product and introduction of new products will be more difficult.

The savings in direct labor are substantial. But, the main feature of the normative component insertion operation is the ability of the inserter to test the component before it inserts the component into the PCB. This feature can be added on to the present component insertion operation. If it is added on, the quality of the PCB's emerging from the assembly operation would be similar to that of the normative operation; but the difference in the complexity of the detailed production scheduling would be much less than the normative operation.

Second, the reduction in buffer inventory between the work centers will cause the scheduling of production to become more difficult. The concentration of the production scheduling decision at the mouth of the component insertion operation is simpler than what occurs today. However, there must be more work done in this area to ensure that it is feasible.

The reduction in the number of batch/queue cells will occur as the manufacturing cycle time is reduced. The normative component insertion operation increases capacity slightly. The main advantage to this configuration is the savings in labor. So, if the quality level of PCB's emerging from the assembly operation increased, the task of detailed scheduling would become easier.

Final Comment

Many benefits will follow from this capacity expansion project. However, the financial benefits may be at the expense of production flexibility. Certainly, the labor requirements will remain stable over a wide range of production volume, but a change to the production mix may cause the performance of the normative component insertion operation to decrease. Also, the normative operation does not allow quick changes to be made to the existing product, nor does it allow short short time spans to introduce new product.

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