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# OPERATIONS MODEL FOR HIGH-VOLUME PRODUCTION LINE

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## ABSTRACT

Printed circuit board test and repair operations for a high volume production line were modeled during implementation in order to evaluate potential performance under various management decision alternatives. Applying modified rules regarding product flow logic and test station assignment resulted in a 23% increase in throughput.

The model utilizes a combined network and discrete event approach written under the SLAM II simulation language framework. The network portion is used to model the test stations, while the discrete event portion allows for actual source code substitution of the AS/RS scheduling algorithm used in simulating the logic and movements of the AS/RS.

## 1. INTRODUCTION

The Line Card Production Module at Northern Telecom, Research Triangle Park, N.C. is a high-volume, printed circuit board production line. The line card itself is a component of the DMS-100 digital switching system which provides the interface between the Central Office and the subscriber. The Line Card Production Module is highly automated utilizing robotics, laser optical scanners, automated test equipment (ATE), and a sophisticated process control network.

There are two major sections of the Line Card Production Module; the Assembly Module, and the **Test and Repair Module**. The Assembly Module is responsible for populating the base printed circuit board with the various components, utilizing robotic insertion and surface mount technology. The Test and Repair Module performs both in-circuit and functional tests on the line cards, and any electrical defects resulting in a test failure are resolved, repaired, and resubmitted for testing. Within the Test and Repair Module, an **Automated Storage/Retrieval System (AS/RS)** transports the line cards through the various test and repair stations. This Test and Repair Module conforms to Bellcore Standard 1000 quality specifications and therefore the line cards produced by the Line Card Production Module are not required to undergo traditional acceptance sampling.

During implementation of the Production Module, operations managers were concerned with improving their understanding of the factors influencing performance and in exploring alternative rules to assure achieving maximum potential throughput.

## 2. SYSTEM DESCRIPTION

The Test and Repair Module essentially performs two major tests. The in-circuit test determines the presence, orientation, and electrical integrity of the individual components and their interconnection. The functional test determines the ability of the line card to perform the tasks it was designed to perform, and its ability to withstand certain adverse conditions. If a line card should fail either test, it is sent to an appropriate troubleshoot and repair station; and once repaired, the line card is again tested before leaving the module. As stated earlier, the Line Card Module is highly automated and virtually all movement of product is via conveyor, AS/RS, and other electro-mechanical transport devices. Manual handling and operator intervention are minimized.

Line cards arrive at the Test and Repair Module and are placed in a carrier which holds 64 Line cards. When an in-circuit test station becomes available, the AS/RS will pick up the full carrier and deliver it to the test station or move it to a holding station.

Once at an in-circuit test station, the line cards are removed from the carrier and tested one at a time. If the line card passes, it is placed in a line card Drawer. (This drawer is similar to the carrier in that it holds 64 line cards, however the line card Drawer itself is the next higher assembly and contains the line cards in the final DMS-100 product.) On the other hand, if a line card fails in-circuit test, it is placed back into the carrier. Once all line cards in the carrier have been tested, the carrier containing the failed line cards are transported to an available in-circuit repair station, another carrier is delivered to the test station, and the cycle begins again. Once the line card Drawer is full of in-circuit passed line cards, the AS/RS moves it to a functional test station or to a waiting station.

Below is a diagram showing the basic layout of the Test and Repair Module test stations relative to the AS/RS. Items labeled IC-1 through IC-6 represent the respective locations of the In-Circuit Test stations. Items labeled F-1 through F-8 represent the respective locations of the Functional Test stations.

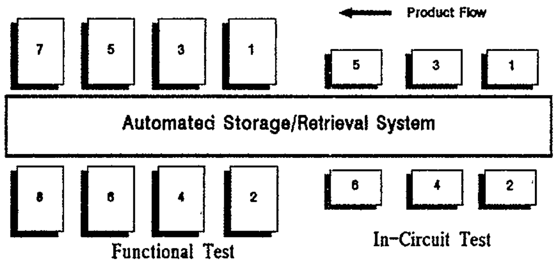


Figure 1: Line Card Test and Repair Module Facility Layout

When a functional test station is available and a line card drawer has been delivered, the entire drawer is tested as a functional unit. If a drawer passes the functional test, it is delivered to semi-finished goods (a holding area for audit and accounting purposes). Should any one or more line cards fail, the entire drawer is rejected and is delivered to a functional repair station. Here, a video display of the failed line cards is presented to the technician. The failed line cards are removed from the drawer and replaced The drawer is then re-submitted for functional test at an available test station. The number of times a drawer may cycle through the functional test/repair loop can be arbitrarily determined.

## 3. MODEL DESCRIPTION

The purpose of the model was to provide an operational tool for the management of the Test and Repair Module, a component of the Line Card Production Module. The purpose of the model was to:

- predict throughput for changes in known or expected operational parameters,
- verify equipment reconfigurations,
- evaluate the efficiency of AS/RS scheduling algorithms, and
- facilitate throughput stress analysis and bottleneck resolution.

Sources of variation affecting the model's ability to predict throughput include:

- individual drawer test time,
- diagnosis and repair time,
- card/drawer failure pattern,
- number of defects per drawer,
- card/drawer arrival interval,
- and AS/RS algorithm performance.

The model begins its simulation by reading a data file containing 52 operational parameters, including:

- product mix percentages,
- test station configuration,
- status of test stations,
- test durations,
- yields,
- line card arrival rates,
- distributions of test failures, and
- initial state of the system.

Once these parameters have been read in, the model will start exercising an AS/RS scheduling algorithm. Entities then begin moving from node to node in the network under control of the concurrently running AS/RS scheduling algorithm. All of the test stations are modeled using the network approach. Each test station is capable of stand-alone simulation with minor changes. There is a maximum of 6 in-circuit test stations, 6 in-circuit repair stations, 8 functional test stations, and 6 functional repair stations. The model can accommodate stations being on-line (active) or off-line (inactive). In addition, the model can simulate equipment failure and/or station preventive maintenance. In network modeling, symbols are used to represent certain operations. SLAM II expands the flexibility of network modeling by allowing the user to re-define a symbol type to meet a specific need.

For example, the SLAM II AWAIT node will queue entities waiting for a specified number of resource units or until a specified gate is opened. Alternatively, the modeler is able to branch into a discrete event routine and define unique conditions for entity release by the AWAIT node. This alternative was necessary in defining product flow through the In-Circuit Test area due to the number of variables affecting the arrival and departure of line cards.

Modeling of the AS/RS was accomplished by inserting the actual AS/RS scheduling algorithm into a discrete event program module. This approach allowed easy testing and analysis of various algorithms and logic options and their effects on the overall system. The scheduling algorithm simulated movement of the carriers and drawers through the Test and Repair Module based on "move class priorities". For example, carriers waiting for in-circuit test represent one class of move, and drawers waiting for functional test are in another type of move class, and so forth. For each move class, the scheduler will attempt to make all possible moves; and then the schedular will drop to the next priority and begin attempting moves. The specific priorities are completely programmable, and experience has shown that priority assignments need to change depending on the dynamic environment of the Test and Repair Module.

The following chart depicts the specific areas modeled and the approach used.

| Network | Discrete |
|---|---|
| Test Stations<br>Repair Stations<br>Product Yield<br>Machine Downtime<br>Configuration<br>Quality Assurance<br>Drawer Creation<br>Storage<br>Statistics Collection | AS/RS Algorithm |

Figure 2: Modeling Approaches Used in Operations Model

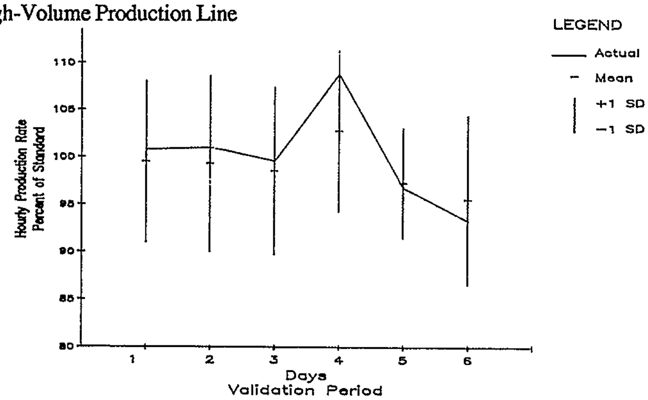


Figure 3: Model Accuracy

In the actual system, an AS/RS move is actuated by a Fortran subroutine call to the AS/RS controller. In the model, however, the AS/RS simulation required unusual logic manipulation in order to allow the simulation clock to advance. This involves first saving the characteristics of the entity, deleting the entity from the source queue, saving the current algorithm location, scheduling the arrival event of the entity at the destination node, exiting the event routine (this allowed the simulation clock to update), reentering the event routine, placing the entity in the desired node, and finally returning to the current algorithm location. This basic sequence of events was modified to accommodate a total of 12 distinct move classes.

Refer to Appendix A for an example of code necessary to simulate the AS/RS moving drawers from in-circuit to functional test.

## 4. VALIDATION

Because the system being modeled was already in existence, a trace-driven validation approach was used to determine the accuracy of the model. The single most important factor was product throughput; therefore, the measure of accuracy was based on the model's ability to predict module output under a set of existing environmental parameters.

The validation period ran for 6 consecutive production days. The simulation was set up to duplicate an 8-hour production shift. Each simulation run included a warm-up period equivalent to 20 minutes real time to allow the model to load various stations. The simulation run for each shift was repeated 5 times to estimate the variance of simulation results. The average hourly output of the five repetitions was used to compare against the actual for that day. In the real system, the shifts were not always exactly eight hours. Actual production shift durations ranged from 7 to 9.5 hours. Instead of readjusting the simulation time, an average per hour rate was determined for the actual system and compared against the simulated per hour rate.

Figure 3 shows that the actual production rates were well within one standard deviation of the simulated estimate. Thus the simulation closely approximated the actual performance for operational use. The production rates are based on specific output quantities, but they are shown only as a percent of the standard production rate in order to mask the production levels achieved at that time.

During the validation period an interesting trend developed. For the first 4 days, the model consistently predicted a lower throughput than was actually realized, most notably on the 4th day. Upon investigation into the matter, it was discovered that the production floor personnel had modified certain procedures on that Friday and the conditions assumed for the simulation did not reflect the changes. The practice was returned to normal and subsequent predictions were more accurate. Because of the accuracy of the simulation with respect to actual, the model was declared valid and work began on hypothesis testing.

## 5. SIMULATION

Initial work with the model attempted to identify the relative sensitivities of the input parameters. As expected, the single most influential factor affecting module throughput was the AS/RS scheduler. Analysis of module throughput henceforth concentrated on AS/RS move class priorities, delivery methods within a move class, utilization of storage areas for product queueing, and functional test/repair cycles. In particular, two areas of AS/RS behavior are reported here: push vs pull logic concerning product flow, and rules for assignment of drawers to the functional test stations.

### 5.1 Product Flow Logic

When the AS/RS schedular was first released, priority was given to servicing incoming line cards. The theory was to prevent bottlenecking in the assembly area. Basically, the AS/RS service priority was as follows:

1. Incoming line cards
2. In-Circuit Test Arrivals
3. In-Circuit Arrival Storage
4. In-Circuit Test Area Departures
5. Functional Test Arrivals
6. Functional Arrival Storage
7. Repair Area Arrivals
8. Storage Removals
9. Module Departures

This approach worked fine when the module was in a start-up environment, however as the module stabilized, product was backing up into the storage areas and not being moved out of the module. For example, a drawer which had completed in-circuit test was picked-up by the AS/RS; only then was a search made for an available functional test station. If one was not available, the drawer was placed in storage. Similar instances occurred for other move classes. Since the removal of drawers from storage was low in priority relative to the other move classes, drawers tended to remain in storage and required manual intervention to re-enter the test cycle. This type of product flow philosophy is know as a push system.

A variety of AS/RS modifications were made in the model to attempt to improve the throughput and reduce the number of drawers being sent to storage. Ultimately the entire philosophy of the algorithm was re-defined. Instead of "pushing" the product through the module, the AS/RS algorithm was enhanced to "pull" the product through. That is, in the above example, the drawer would not leave the in-circuit test station until a functional test station was available. Storage was eliminated, and the following move priorities were established:

1. Module Departures
2. Functional Test Arrivals from In-Circuit Test
3. Functional Test Arrivals from Repair
4. In-Circuit Test Arrivals from Module Entry
5. In-Circuit Test Arrivals from Repair
6. Module Arrivals from Assembly

The alternative AS/RS scheduling algorithm was debugged and tested using the model. Due to the massive change in product flow philosophy, numerous presentations were given using the simulation analysis results as proof of validity. The new algorithm was loaded into the AS/RS control where it performed as expected and without further modification.

### 5.2 Assignment Rules

The other major area of AS/RS behavior studied envolved the selection method used to deliver drawers to the functional test stations. The original search method searched for an available functional test station in a linear fashion; that is, functional test station #1 is checked for availability first, then station #2, then station #3, and so forth. This search pattern was used for all drawers destined for functional test whether they came from an in-circuit test station or a functional repair station. Normally, a full functional test cycle for a drawer takes approximately 20 minutes. However, drawers coming from a functional repair station need only to retest the specific cards that failed the previous functional test. Depending on the actual number of previously failed cards, the retest takes approximately 4 to 8 minutes.

There were basically two problems identified with the original method of drawer delivery to the functional test stations; specifically station utilization and contention. Because of the linear search pattern, delivery of drawers to the functional test stations was not evenly distributed. Utilization of the functional test stations varied from an average of 95% on station #1 to less than 5% on station #8. Also, the AS/RS selected a functional test station for drawers arriving from functional repair in the same linear fashion as drawers arriving from in-circuit test, therefore drawers requiring only 4 to 8 minutes of a resource (specifically the functional test station) were competing with the drawers requiring 20 minutes of the same resource. The throughput of the retest drawers was being slowed due to resource contention.

A variety of scheduler modifications were tried and tested on the model. The particular modification which was implemented on the actual system retained the linear search pattern, with a minor twist. The drawers leaving in-circuit test checked functional test station availability in the usual fashion, however, the drawers leaving the functional repair area searched for an available functional test station in reverse order. That is, drawers leaving in-circuit test searched functional test station #1, then station #2, and so forth; drawers returning from functional repair searched functional test station #8 first, then station #7, and so forth. With this search algorithm, 4 to 8 minute test sessions were not competing for the same resource as 20 minute test sessions.

### 5.3 Other Areas of Simulation

In an effort to further increase throughput, potential bottlenecks were investigated. When the functional test cycle time was decreased in the model, the simulation runs showed an overall decrease in functional test area utilization, with no change in either the in-circuit test area utilization or the module throughput.

The in-circuit test cycle is relatively short, and the cards are tested individually. Therefore, product handling is a major factor influencing performance. When cards enter the Test and Repair Module they are placed in drawers. At in-circuit test, the cards are removed from the drawer, tested, and replaced one at a time. Thus even small changes in the handling time affected throughput significantly.

## 6. RESULTS

The benefits obtained from this simulation project can best be classified as oriented toward either operational or technique considerations. Operational results are those which directly satisfy the objective of the modeling project, that is, to improve management insight and decisions to increase the throughput of the module. Findings related to technique are not quite as tangible, but they provide insight into the system under study and the simulation process itself.

### 6.1 Operational Results

**Predicting Output:** The average hourly throughput of the Test and Repair Module increased by 23% after applying improved rules based on analysis of alternatives using the simulation model.

**AS/RS Algorithm:** By far, the most influential modifications affecting module throughput were those made to the AS/RS algorithm. Using the reverse search assignment rule allowed for an abbreviated functional retest and eliminated interference with product being assigned to initial test. The scheduling algorithm modification to determine flow by a pull philosophy reduced waiting time for both initial and retest operations.

**Bottleneck and Configuration:** Options were evaluated to reconfigure the Module so that the cards can be tested before they are placed in drawers. Options have been tested on the model and a number of reconfiguration plans have proved to be viable. One configuration in particular calls for relocating the in-circuit test stations outside the Test and Repair Module whereby the individual cards are inspected and in-circuit tested immediately after assembly. They are then placed in the drawers and transported to the Module for functional testing.

### 6.2 Technique Findings

This and other simulation projects provide beneficial results that cannot be measured in quantitative terms. The development of this model resulted in an extensive expansion of knowledge regarding application of the SLAM II/TESS simulation system. This knowledge extended into a better understanding of the model building process, variance reduction techniques, validation methods, and limitations of simulation.

Because the AS/RS scheduling algorithm was simulated by discrete modeling, comparative analysis among the various algorithm strategies was simplified. Substitution of the scheduling algorithm file directly into the model reduced set up and turnaround time for simulation runs. SLAM II library functions allowed for easy transition between the network and discrete event portions of the model. Graphic capabilities of TESS enhanced the capability to stress important output factors, thus providing a positive influence on management understanding and decisions.

## 7. CONCLUSIONS

The model developed for the Test and Repair Module operation is an accurate predictor of product throughput when used for "what if" type analysis. The model has been used to verify equipment configurations, detect bottlenecks, perform stress analysis, and evaluate the efficiency of the AS/RS scheduling algorithm. Future enhancements considered include refinement of the model to include peripheral activities (e.g., quality control, material handling), improvement of ability make parameter changes, and development of animation and graphics macros for analysis and presentation purposes.

## APPENDIX A: SCHEDULER ALGORITHM

Moving drawers from the in-circuit test area to the functional test area is dependent upon 1) the presence of drawers to be moved, and 2) the availablilty and configuration of functional test stations.

```
BEGIN
FOR (each in-circuit test station) DO
   BEGIN
   Check for completed drawer
   IF (drawer completed) THEN
      add test station to snapshop array
   END

Current Label:
FOR (each station in snapshop array) DO
   BEGIN
   Copy attributes of entity (drawer)
   FOR (each functional test station) DO
      BEGIN
      IF (available and configed) THEN
         BEGIN
         Remove drawer from in-circuit
           station
         Save drawer destination
         Save current label
         Schedule drawer arrival
         Exit EVENT routine
         END
      END
   END
END.
```

Upon re-entering the EVENT routine after ocating a suitable drawer destination, the following server function is executed:

```
BEGIN
   Place drawer in destination queue
   GOTO (current label)
END
```

## REFERENCES

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