Progressive Hand Assembly of Circuit Packs in a Small-Lot, High-Mix Environment

W. Andrew Elliott

Progressive assembly is widely used to hand-assemble components on circuit packs. However, this method is normally used whenever lot sizes are large and the production volume is high enough to justify the effort required to set up the operation. When the manufacturing environment consists of small lot sizes and many circuit pack codes, progressive assembly is usually not the method of choice. It is a manufacturing truism that the benefits of progressive hand assembly do not extend to small-lot production where many code changeovers and setups are required. The prevailing view is that the benefits derived do not exceed the effort required to prepare and update the manufacturing information for each circuit pack type. This paper describes the application of progressive hand assembly to a manufacturing shop that typifies small-lot production and high product variability. It shows that the benefits from a high-volume operation can be achieved in a small-lot operation when component preforming, kitting, and setup issues are appropriately addressed.

Introduction

The circuit pack assembly operation described in this paper is representative of the small-lot, high-mix environment. The average lot size—i.e., the quantity of circuit packs of the same type to be assembled as a group—is 25 packs; the minimum is one pack. (*High-mix* indicates a large variety of circuit pack types to be assembled.)

Figure 1 shows the circuit pack assembly and test process flow. More than 180 active circuit pack codes (i.e., types) are assembled and tested. Not all process steps shown apply to all circuit pack codes. Table I shows that few, if any, of the codes can be considered high-running, and that the majority have annual volumes under 200 packs. The annual volume is distributed over 12 months based on customer orders. There are over 40 board profile sizes plus 6 daughter board profiles. (A "daughter board" is a subassembly that is placed on a "parent" board.)

Traditionally, bench operators assemble circuit packs after the components have been hand-inserted. When the first pack is done, the second pack is begun, and so on, until the lot is assembled. A bench assembly operator seldom sees a familiar circuit pack type, and the effect is similar to building each type for the first time. The operator must correctly select, locate, form, cut, and clinch the leads of each hand-inserted component. (*Clinching* is a process of flattening the protruding lead against the solder pad.) With about 25 boards to a lot, and with as many as 84 components per board, the operator cannot reach a level of knowledge that comes from familiarity.

Traditional "build complete" assembly requires several operator skills, including component identification, lead preforming, and manually tack-soldering components that cannot have their leads clinched. But because training and operator turnover must be dealt with continually to maintain a capable workforce, traditional hand assembly methods cannot provide the necessary quality level.

Compared to traditional hand assembly, progressive hand assembly (see Panel 1) normally overcomes these difficulties, while offering the unskilled operator a job in which productivity is almost immediate. The

Panel 1. Progressive Assembly

Progressive assembly is a systematic method to manually assemble circuit pack components, using several operators to sequentially assemble the circuit packs. Each operator assembles the same few components on each pack, reducing the complexity of the job. And each operator's work is checked by the next operator, resulting in immediate feedback of quality problems. The conveyor provides a pacing effect that improves concentration and productivity. Since the packs are fed by conveyor into the wave solder machine, handling problems are minimized.

The major benefits of progressive assembly are:

- *Improved quality.* Hand assembly has one of the highest defect rates in a circuit pack assembly shop, and conversion to progressive hand assembly can significantly improve quality.
- *Reduced manufacturing interval.* Reductions from days to hours are common.
- *Increased productivity.* Assembly effort is greatly reduced because the circuit pack is not repeatedly picked up and turned over, and leads are not clinched and cut to proper length. Reduced handling also improves both productivity and quality.

operator-check-operator aspect (i.e., each successive operator on the line inspects the work of the operator immediately before) allows immediate error detection and correction, further contributing to improved productivity.

Progressive assembly significantly reduces the effort associated with traditional hand assembly. Most of the reduction comes from eliminating having to turn the board over after the component is inserted; then having to locate, cut, and clinch the leads; and finally having to turn the board over again to insert the next component.

Progressive hand assembly also provides important benefits over alternative methods of assembly when non-machine-insertable components must be placed on a circuit pack.

- The manufacturing interval can be minimized by keeping the product in continuous motion, rather than sitting in a queue waiting for the next process.
- Quality is usually higher when compared with the alternative method of hand assembly by an individual operator at a bench.
- Quality often is also better than in semiautomatic machine-assisted hand assembly, where individual packs risk handling damage from loading into the machine, unloading, and racking.
- Productivity is maximized by providing a steady supply of work.

Table I. Circuit Pack Volumes and Variety in the Typical Small-Lot, High-Mix Environment

Annual Volume	Number of Codes
1-200	92
201-500	35
501-1000	24
1001-2000	23
2001-3000	4
3001-5000	4
5001-7500	2
40 board sizes, plus 6 daughter board profiles	

The benefits are usually realized in high-volume, large-lot production. Because few code changeovers are necessary, downtime is rare. The operators build the same circuit pack repeatedly, and assembly lines usually can be kept moving. The work is uncomplicated, and the operators can focus on the few components for which they are responsible, thereby minimizing errors. And because each operator's work is checked by the next operator as the pack moves down the line, any errors should be caught almost at once.

In a small-lot operation, code changeovers occur frequently, and downtime to set up the new code must be minimized. When workers are idle during setup for the next code, productivity suffers. Each code change presents new information to the operator about different components, their locations on the board, and new assembly instructions. This new information can lead to quality problems if the operators do not quickly assimilate it. As in large-volume progressive assembly, the components must be properly preformed to make sure they fit the holes with a minimum of effort. Leads must be cut to the proper length to avoid an additional step—lead-trimming—after wave soldering. Finally, the kitting operation must have been carefully performed to ensure that the kitting trays contain enough correct components. (Kitting is the process of preparing component sets for a particular

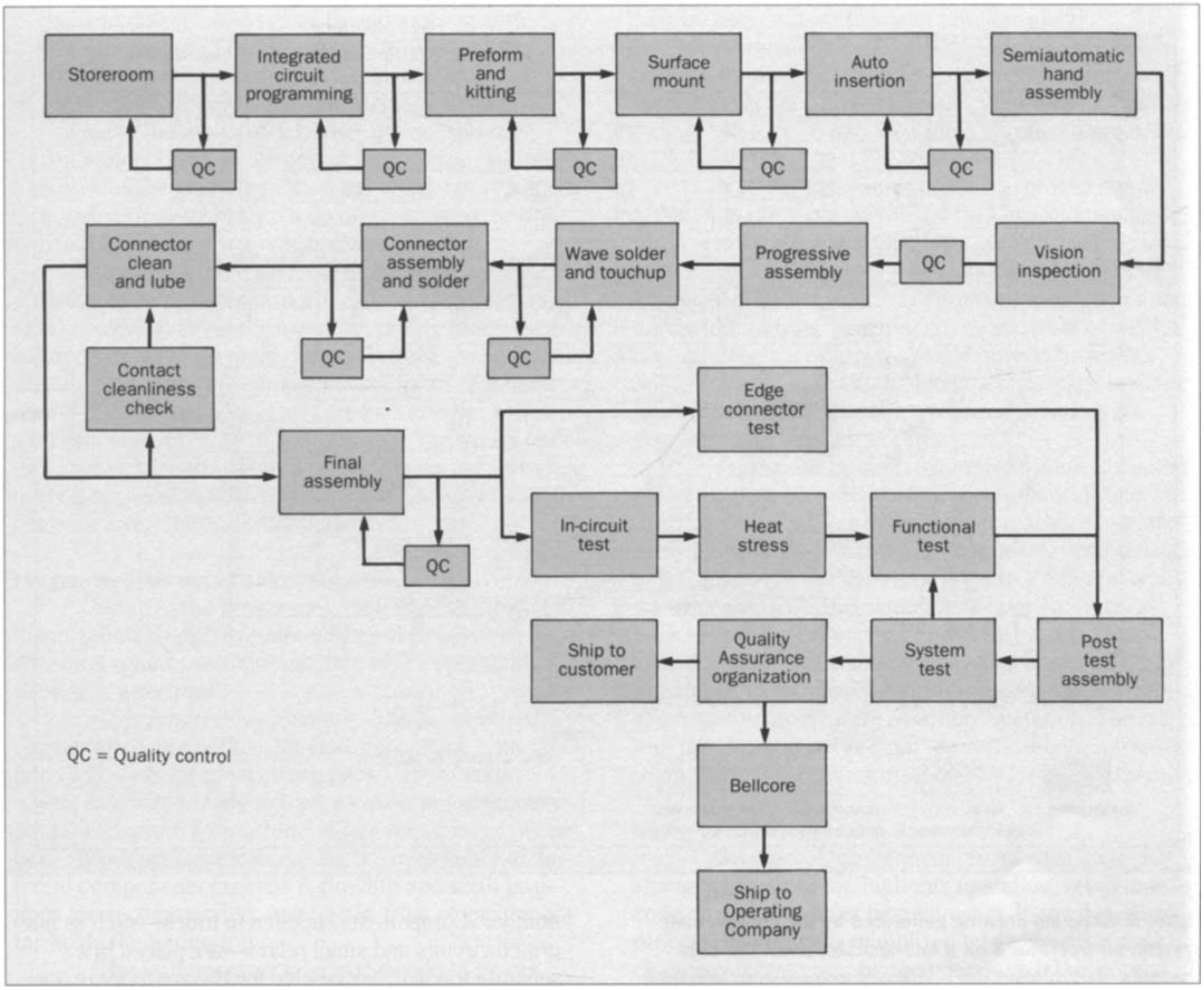

Figure 1. Circuit pack assembly and test process.

manufacturing process.)

Given the efficacy of progressive assembly in large-lot, high-volume environments, the questions that remain are:

- Would the benefits be worth the engineering effort to prepare and maintain the circuit pack codes for progressive assembly?
- Would the benefits of progressive assembly apply to the small-lot, high-mix environment?

Engineering the Progressive Assembly Process

Considerable preliminary engineering effort is needed to prepare a circuit pack code for progressive assembly. The following considerations apply:

- *Line balancing*: the time to manually insert components into a circuit board must be balanced among the operators to equally distribute the component insertion times. This includes checks of the previous operator's work and time for the last operator to check his or her own work.
- *Component preforming*: as part of the process to

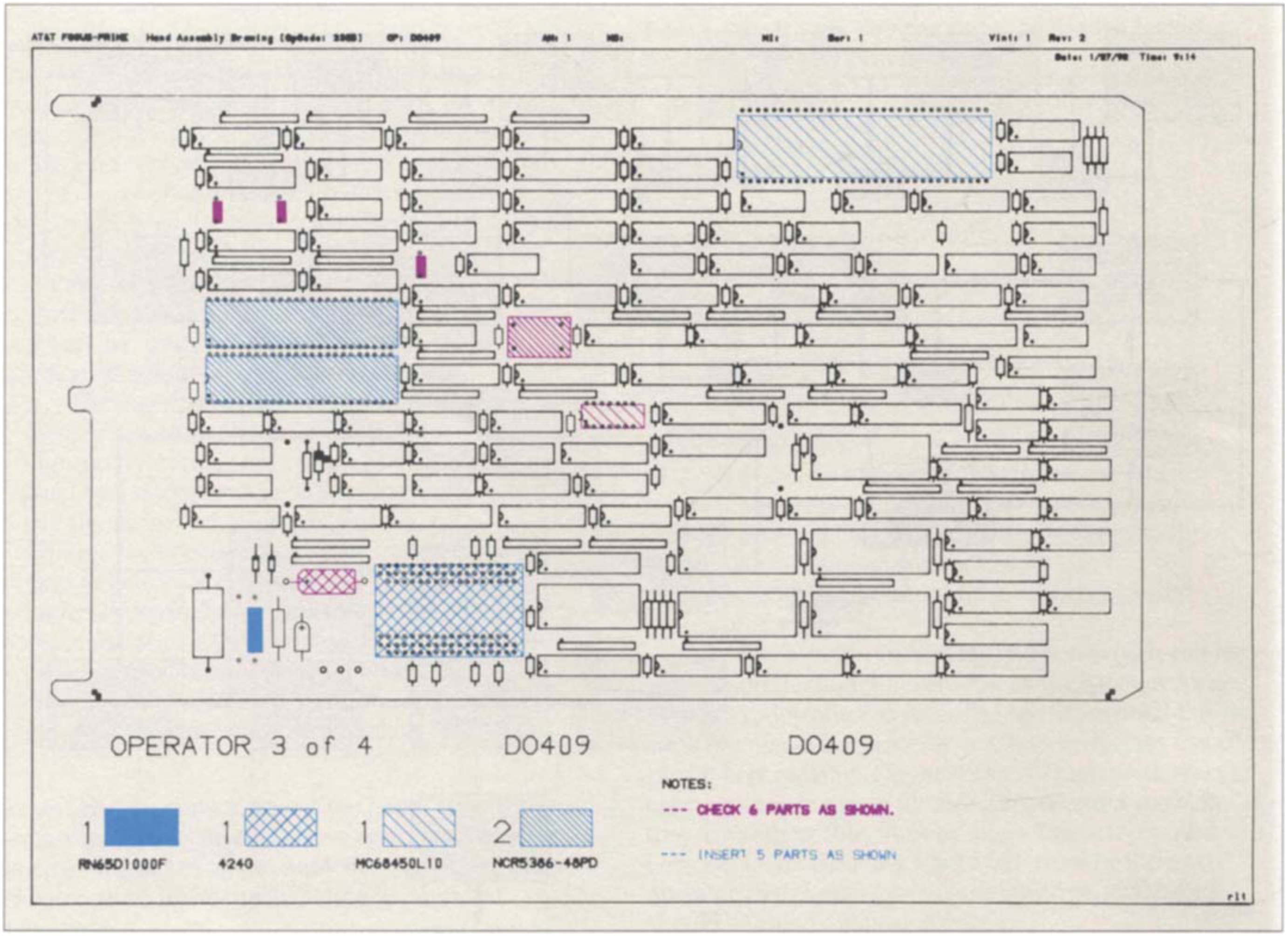

Figure 2. Shop aid drawing generated by the FOCUS-PRIME system, for Operator 3 on a four-operator line. The blue shadings identify the third operator's components and their locations. The parts assembled immediately before, by Operator 2, are indicated by purple shading.

prepare a code for progressive assembly, each component is analyzed to determine its proper lead form and length. Control of lead length is necessary because excessively long leads must be cut after wave soldering at an extra cost.

- *Kitting*: Components for a given progressive assembly operator are placed in individual bins (or compartments) in a single tray, and all components are labeled with a description, and with the operator, tray, and bin number. Components supplied in tubes—such as integrated circuits and small relays—are placed in a separate tray and are labeled for the appropriate operator. Some other parts are kept in the supplier's original packaging to minimize damage.
- *Shop aids*: these are pictorial views of the circuit pack (including assembly information) needed by each operator. They are generated by two methods. The FOCUS-PRIME system[1] provides shop aids for supported circuit pack codes (see Figure 2). For other codes, a system developed at the Columbus Works (the Scandhu System) provides shop aid drawings. In either instance, drawings are color-coded and customized for each operator. To aid in the operator-check-operator function, shop aid drawings always use *purple* to iden-

tify components inserted by the previous operator, and each operator has his or her own "customized" shop aid drawings to know what to look for.

- *Information management*: considerable effort is needed to maintain the accuracy of line balancing, component preforming, kitting information, and shop aids. Changes may be suggested by operators, recommended by engineers to improve processes, or mandated by engineering design changes.

In a small-lot, high-mix environment, careful attention to component preforming, kitting, and shop aids is essential to ensure a smooth progressive assembly operation. Disruptions can result from wrong or mixed parts, incorrect component preforms that make the operator struggle to insert the part into the board, a shortage of parts, or parts identified for the wrong operator. To minimize the disruptive effect of parts shortages, a stock of spare parts is maintained in a nearby computer-controlled storage and retrieval system.

Progressive Assembly Line Operation

Setup of the progressive assembly line itself to manufacture changing codes is also an issue. To discuss the setup issues, an understanding of the operation of the line is beneficial.

This progressive assembly line is a powered, conveyorized line with six operator positions. Four positions will serve for most circuit packs, as concerted efforts have been made to have as many components as possible inserted by machine. When the number of components per operator exceeds 12, or the number of different components exceeds 6, the fifth and sixth positions are recommended. A recess in front of each operator holds the kitting tray.

The lead operator selects the code to be run from a menu on the host computer. The dwell time (i.e., the amount of time the circuit pack remains stationary in front of the operator) and assembly line width (i.e., the width of the four conveyor sections) are downloaded to the programmable controller that operates the line. If the width differs from the present line width, the rear conveyor rail automatically adjusts. If packs are already on the line, the adjustment is made as soon as the packs leave the first conveyor section (the third operator position), providing sequential width adjustment. The width of the four conveyor sections is sequentially adjusted under computer control. If no packs are on the line, all four sections will width-adjust simultaneously.

A few seconds before the pack is scheduled to move, a warning light flashes to inform the operator. If more time is needed, the operator presses a foot switch to hold the pack. When the switch is pressed again, the pack is released.

If solder masking is needed to protect some holes from the solder wave, the lead operator applies this mask in either liquid or tape form, and places the circuit pack in a solder fixture (i.e., pallet) that allows circuit boards of different widths to be accommodated in a standard width fixture. This reduces the number of width adjustments that otherwise would have to be made. Solder fixtures have eliminated board warpage resulting from wave soldering, and have helped maintain consistently superior solder quality.

Following the sixth operator position is a vertical buffer system. The vertical buffer automatically stores up to 25 circuit packs if the wave solder machine is temporarily unavailable because of adjustment or maintenance, or if the wave solder conveyor is set to a different width for soldering boards assembled off-line. The vertical buffer system—not normally used with a progressive assembly line—is invaluable in a small-lot operation to prevent short-term solder machine unavailability from affecting the progressive assembly operation. The incline unit takes circuit packs from the vertical buffer, transports them to the wave solder machine, and transfers them.

Setup of the Progressive Assembly Line

Because of the frequent circuit pack code changes in a small-lot, high-mix operation, setup time for code changeover must be minimized. In the described process, downtime is minimized by dividing the code changeover tasks among the operators. If these were performed by one typical operator, the tasks would take much longer than the four to five minutes needed by all four operators cooperatively. Setup responsibilities are as follows:

- *Operator 1*: Moves the process cart for the new lot into position, selects new code from host computer menu, obtains needed materials shown on the shop aid, and returns unneeded materials from previous lot.
- *Operator 2*: Ensures adequate supply of solder fixtures; picks up empty kitting trays, and places them on cart for return to kitting area; and provides kitting trays for new code to Operators 1 and 2.

- *Operator 3*: Picks up shop aids from previous code and refiles them in filing cabinet adjacent to the line; distributes shop aids for new code.
- *Operator 4*: Distributes kitting trays for new code to Operators 3 and 4.

Operator 1 begins the setup sequence while the other operators are finishing the present lot. As each operator completes work on the present lot, the setup activity is started. By the time Operator 4 has completed his or her activity, the new lot is already on the assembly line.

The simultaneous actions of the four operators reduce internal setup time, i.e., the time when the process must be shut down to allow for changeover to the next code. If too many setups are required, or if too much time is taken per setup, the capacity of the line could be reduced below the required level. To minimize internal setup time, no lead preforming is done at the line. Lead preforming and kitting are done offline, while the process is running. Internal setup time reduces the capacity of the operation.

Benefits in the Small-Lot, High-Mix Environment

Installing progressive assembly in a small-lot, high-mix environment led to an 85 percent improvement over the defect rate for "build complete" hand assembly. Productivity improved 75 percent over the earlier assembly method, after needless handling of the circuit board to cut and clinch the leads was eliminated, and after racking and unracking the boards was ended.

Another major benefit of progressive assembly in the small-lot, high-mix environment was that the manufacturing interval for the manual assembly operation was reduced 75 percent. This resulted from lots no longer spending time in hand assembly, and in the lots waiting in buffers for inspection and quality checking operations.

These benefits have brought about a new manufacturing philosophy. Before progressive assembly, it was advisable to move every possible component from hand assembly to machine insertion, even if this move required an extra setup, and even if only one part was inserted, to obtain the quality improvement available from this method. It is now viewed as more sensible—if fewer than four components are inserted at a particular machine—to eliminate a machine insertion step and move the components to progressive assembly. This reduces the queue time and its effect on manufacturing interval, decreases the demand for machine insertion facilities, and eliminates unnecessary handling.

Summary

Progressive hand assembly of circuit packs is applicable to the manufacturing environment characterized by high product variability and small lot sizes. The same benefits normally associated with high volume and low variability also occur in this environment. More engineering effort is required, however, to deal with the number of codes that must be assembled. The process described in this paper has exceeded expectations for quality improvement, productivity improvement, and manufacturing interval reduction.

There are also synergies that lead to further improvements. For example, the shorter manufacturing interval gives quicker access to defect information. Shorter intervals tend to generate less inventory; and less inventory makes the process both more visible and amenable to further process improvement.

Acknowledgments

Successful implementation of this process depended upon many people. Particular mention should be made of the contributions of Todd Fisher, Charlie Hoben, Don Hurley, Ron Jones, Jon Miller, Mike Smith, and Dave Cianelli, who originally suggested the project.

Reference

1. William A. Burling, Barbara J. Bartels Lax, Lawrence A. O'Neill, and Thomas P. Pennino, "Product Design and Introduction Support Systems," *AT&T Technical Journal*, Vol. 66, Number 5, September/October 1987, pp. 21-38.

***W. Andrew Elliott** is a distinguished member of technical staff in the Operations Systems Manufacturing and Product Engineering department of AT&T Network Systems, Columbus, Ohio. He is responsible for process engineering of circuit pack assembly for Operations Systems products. He joined AT&T in 1967 with a B.S.E.E. from Ohio University, Athens, and earned an M.S. in metallurgy and materials science from Lehigh University, Allentown, Pennsylvania.*

(Manuscript received December 2, 1991)