Setup Time Reduction for Electronics Assembly: Combining Simple (SMED) and Sophisticated Methods

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Abstract

Setups determine downtime, capacity, product quality, and to some extent costs. As much as 50% of effective capacity can be lost to setups in some electronics assembly.

In this paper we show that large reductions in setup time are possible for electronics assembly. We use a two-part approach. The first part consists of classic process re-engineering using "Single Minute Exchange of Dies" (SMED) concepts developed by Shigeo Shingo for metal fabrication. The second part uses a sophisticated factory information system, with hand-held wireless computers and barcode scanners, to further reduce setup times and increase setup accuracy. This two-part approach gave a reduction of about 86% in key setup times, plus labor savings, quality improvements and other benefits. One narrow measure of performance gave an order of magnitude improvement.

Our results show that SMED is applicable well outside its traditional domains such as stamping and metal-working. We confirm that the seemingly extreme benefits claimed by SMED advocates are achievable, but only with the assistance of modern information technology. In our case the initial investment of $350,000 led to a ten-fold larger net present value.

Setup Time Reduction for Electronics Assembly: Combining Simple (SMED) and Sophisticated Methods

This paper examines setup time reduction for printed circuit boards (PCB) assembly in the electronics industry. PCBs are basic building block of electronics with one or more in virtually every electrically powered device. Setups are vital because they determine downtime, capacity, product quality, and to some extent costs. Errors in setups lead to incorrect components or incorrect placement on the boards, requiring manual diagnosis and rework. We used a rapidly growing PCB assembly operation to conduct setup time reduction. The approach consisted of two parts. The first part used classic, common sense "Single Minute Exchange of Dies" (SMED) concepts taken from metal fabrication (Shingo, 1985). These are akin to "re-engineering" the setup process. The second part developed a sophisticated factory part information system, with hand-held wireless barcode computers, to further reduce setup times and increase setup accuracy. This two-part approach resulted in a better than 5 fold reduction in key setup times, plus labor savings, quality improvements, and other benefits.

Section 1 of this paper reviews the setup problem and the setup reduction literature in various industries. Section 2 describes the technology of assembly and setups for printed circuit board assembly. Section 3 describes how SMED concepts can be applied to these setups. Section 4 introduces the computerized information system. Section 5 documents the results. Section 6 discusses additional work that can be done to further reduce setup times.

Section 1 Introduction

Setups, in the printed circuit board assembly industry, can be exceedingly time consuming operations. Manufacturers of surface mount technology printed circuit board assemblies report that setup times consume as much as 50% of the total production time (Sadiq and Landers, 1991).

Long setup times increase inventory levels, reduce capacity when lines are idle during setup, and affect direct labor. Though operators performing the setups are busy, downstream assembly operations must wait for completion of a setup to begin production. This problem can be relieved somewhat by using buffers--racks of completed PCBs ready to be put into mechanical assemblies. Another solution is to stagger the work hours of the operators and the assemblers. Still, setups are not always completed when expected and the buffers create new problems such as longer cycle times.

The under-utilization of expensive capacity is bad enough, but lengthy setups have other undesirable effects on manufacturing resources. One of these is increased inventory as a result of manufacturing in larger lot sizes. Large lot sizes, instituted to reduce the number of setups performed, result in an increase in work-in-process (WIP) and finished goods inventories. Consistent with EOQ, production schedulers and planners frequently cite setup costs as a major factor in determining lot sizes. This was observed at our site and was also reported by Ammons, et al (1992).

Trends toward smaller lot sizes and more setups

Traditionally, American companies used long production runs and large lot sizes, because of the perception that long runs are more efficient. This led to large inventories and longer lead times.

Companies are now moving to smaller lot sizes, in response to forces such as:

- Increased market competition.
- Trends toward just-in-time (JIT) production (Cavinato, 1991).

- The move towards more customized products (Davidow and Malone, 1992). This market trend translates into a need for greater manufacturing flexibility, which is a natural byproduct of setup time reduction.
- The need for production flexibility. With more frequent but smaller lots, a factory can modify its build schedule more easily.

Setup reduction is a key factor in the successful implementation of JIT production (Fiedler, et al 1993; Hall, 1983; Hay, 1989; Mirza and Malstrom, 1994). Lot sizes become smaller while the number of lots produced becomes greater. Handfield (1993) performed a field study to determine the performance measures that distinguished non-JIT from JIT companies. He found that setup time reduction and subsequent lot size reductions were key characteristics of the JIT firms.

General setup time reduction: literature review

There are numerous research articles on setup reduction efforts and strategies. Generally it is treated as a technique within the broader area of JIT production. Porteus (1985) proposes a model to calculate how much to invest in setup reduction. Spence and Porteus (1987) discuss the value of setup time reduction in the implementation of the JIT and Zero Inventory strategies. They also discuss how setup time reduction increases a factory's effective capacity and how to use this capacity to either reduce lot sizes (i.e. perform more setups) or reduce overtime. Esrock (1985), in his paper on setup reduction, gives an exhaustive list of the positive influences of setup time reduction on manufacturing operations.

Cavinato (1991) stresses the importance of setup time reduction in increasing a company's competitive edge. He notes that:

> The ripple effect is tremendous: less storage, less time between production runs, less time customers wait for their goods, more produce-to-order and less produce-to-stock, easier ability to customize goods for customers, and in some instances it is possible to be paid by customers before payment must be made to suppliers.

Hahn, Bragg and Shin (1988) examine the operating characteristics of setup when used as a decision variable in a capacity-constrained environment. Their study demonstrates that setup time reduction is a key way to increase effective capacity. They note that traditionally, American management has treated setup time as a given in its capacity management decisions.

PCB Assembly setup reduction: literature review

The literature on setup reduction efforts in PCB assembly looks almost exclusively at the pick and place machines which put small electronic components onto the boards. The machines are the bottleneck in setups due to their high cost, and the need to place 50 to 200 feeders for each setup. Each component type needs its own feeder, so there is a strong link of PCB complexity to setup time.

There are two basic strategies for speeding setups on these machines: reducing the time needed to set up each feeder, or reducing the number of feeders to be set up. With few exceptions, the literature looks at the second of these. For example, by changing the sequence in which different jobs are run, consecutive jobs can use more of the same components. Jain, et al (1996) review this problem from an optimization perspective, and report on setup issues in several Hewlett-Packard plants. Interestingly, they report that setup "time per feeder" ranges from 1 to 5 minutes, but don't discuss why the range is so large, or how to change it. Many other authors examine optimizing job sequence, often in conjunction with other problems such as optimal placement of feeders (Askin et al, 1994; Crama et al 1997; Gunther et al, 1998; Leon, 1998; Li and Randhawa, 2002).

In this paper, we take the other approach: reducing the time per feeder. Aguayo and Tran (1994) present a system that addresses the time per feeder, speeding the setup verification activities. Their approach is conceptually similar to the second half of our approach.

Single Minute Exchange of Dies: Description and Literature Review

SMED is basically a methodology for systematic and radical reduction of setup times, with documented cases reductions from hours to less than ten minutes ("single [digit] minutes").The SMED methodology consists of two phases. In the first phase, a distinction is made between internal and external setup tasks. Internal setup operations are those that must be performed when the machine is stopped. These operations occur on-line to the machine. External operations are those that can be performed while the machine is in operation. It is more efficient to perform these tasks off-line from the machine. Once the operations are classified as either external and internal, the external operations can be moved off-line to reduce machine downtime.

For example, when analyzing the setups for the large body molding presses at Mazda, the SMED inventor, Shingo (1985) discovered that the presses were shut down while the mounting bolts for the new die were being located. This task was considered part of the internal setup process until Shingo moved it off-line. As a result of this and similar changes, Shingo reduced the on-line setup time for this machine by 50%. Typical activities during this phase include pre-positioning all dies and tools needed for the next setup.

In the second phase of SMED, all aspects of the setup, both internal and external, are streamlined to make them more efficient. Internal setup efficiency results in labor savings and less downtime machine capacity. External efficiency does not directly improve downtime, but gives better utilization of labor.

Since at the factory or line level labor can be a constraint on doing setups, it can also indirectly reduce downtime, as we will illustrate. The methods used are akin to business process re-engineering: look at all the activities that go on, and design faster ways to do them. The new methods often include: replacing general tooling, fixtures, and adjustment mechanisms such as screws with special purpose equivalents which require little or no adjustment, and will only fit in the correct orientation; using color coding and spatial layout to make items easier to find and harder to make errors with; using floating workers who assist machine operators with each setup; pre-stationing or pre-loading raw materials for the next batch. Small, highly specific changes to machines and even to product designs are sometimes used. Wherever possible, “foolproofing” is used to either make errors impossible, make them obvious when they occur, or reduce their effects. (Nakaje and Kume, 1985)

A variety of good practice-oriented material has been written about SMED, including those previously mentioned and Sekine (1992), and Mileham, et al (1999). Almost all published material on SMED uses traditional material processing industries for examples. One exception is Sharma (2001), which discusses PCB assembly. Analytic and comparative articles are rarer. Leschke (1997) looks at the economic costs and benefits of different types of SMED activity. Moxham and Greatbanks (2001) examine a small textile plant and argue that a number of cultural, procedural, and managerial barriers must be overcome before SMED can be implemented. McIntosh, et al (2000) provide a critical discussion.

Section 2 Description of the Manufacturing and Setup Operations

This project improved the setup of printed circuit board (PCB) assembly processes at a San Diego company which is in the communications industry. This company is highly innovative, with new board designs released almost daily to manufacturing for prototyping. As a result, its PCB assembly system is one of high variety produced in medium to small lot sizes (10 to 300 boards per lot, average about 100). Prototype and production boards are done in the same facility.

The factory is housed in a building of approximately 100,000 square feet. There are five hundred employees involved in manufacturing. One hundred and forty of these employees, and over ten million dollars of equipment, directly support printed circuit board assembly.

Process Overview

The board manufacturing process consists of four steps separated by buffers.

1. **Surface mount assembly:** Printed circuit boards are populated with surface mount components, in a highly automated and tightly coupled line process. Typical boards have several hundred surface mount components such as resistors, capacitors, and integrated circuits.

2. **Through-hole assembly:** Most boards receive a small number of through-hole components by manual assembly. After they are inserted, the boards are wave-soldered, tested, and reworked as necessary.

3. **System assembly:** Boards are assembled into functional systems. Each system contains a number of different boards.

4. **Final test:** Because the systems are usually used in outdoor and isolated environments, the finished systems receive extensive functional and environmental testing before they are shipped.

At the inception of the project there were four main board assembly lines. The surface-mount assembly segments had tightly coupled fully automated machines. There were approximately 20 setups per week on the four assembly lines, most of which ran two shifts per day, five days a week. Each setup took approximately two hours per assembly line. During this time, all of the surface mount assembly equipment was idle.

Because the surface mount portion of the process is the most capital intensive and has the longest setups, it was viewed as the key for setup reduction. The PCB process starts with bare printed circuit boards. After printing with solder paste, each board is populated with surface mount components. On each line, two “chip shooters”, high speed automatic placement machines, are used to populate the boards with small components such as resistors, capacitors, inductors, and small integrated circuits. A typical board contains 1,000 components of about 100 types, which is why they are placed by a high speed machine. The Fuji CP6 machines used can place up to 28,000 parts per hour, or 8 per second. Then a single placement machine, which is slower but finer pitch, is used to place the larger packages such as Quad Packs and plastic leaded chip carriers (PLCCs).

Once the boards are populated with components, they are visually inspected, then conveyed into a reflow oven where the boards are heated to reflow the solder.

Setup overview

A normal setup of the surface mount assembly process requires preparing all the machines and the conveyors between them. Conveyors are adjusted to accommodate the width of the next board to be produced. Component feeders are removed from the placement machines and replaced with feeders holding the components needed on the next board. The solder reflow oven is reprogrammed with the temperature and duration settings.

Of all of these setup tasks, the preparation of the component feeders and their placement machines (chip shooters) is the most time consuming. Their overall setup breaks down into two labor intensive processes: setting up the feeders, and loading the feeders onto the machines. A third process is to download the correct software (data files) for the board into each machine. This software describes the order and location of each device to be placed on the board, and usually includes silhouette information for automated visual checking that the correct part has been placed in the correct orientation.

Placement machine setups occur in two discrete processes that may be separated in time by hours to days. The first process is *feeder setup*. It involves locating the component reels needed for a production run and loading them onto custom feeders. This process occurs off-line from the machine and is considered an external process in SMED terminology. The second process is *placement machine setup* and is performed at the machines. In SMED terminology, this is an internal setup process. Many hours were spent observing and interviewing the feeder setup and placement machine operators in order to map out the tasks performed in each process.

Off-line setup

Most of the surface mount components are packaged on component reels. These reels look very similar to movie reels. They come preloaded from component vendors in two standard sizes, 7 and 13 inches in diameter, and several widths for different component sizes. The components are nested between two pieces of tape and wound onto the reel. One reel may contain as many as 10,000 components, which is the reason they are so popular for use with high speed placement machines. Before they can be used, the reels must be loaded onto special feeders, which are designed to fit into the chip shooter machines.

The goal of the feeder setups is to find the correct reels for a batch, mount them on the correct feeders, and pre-position them on racks. The time needed for feeder setups is not fully predictable and feeder setup is therefore usually done several days in advance.

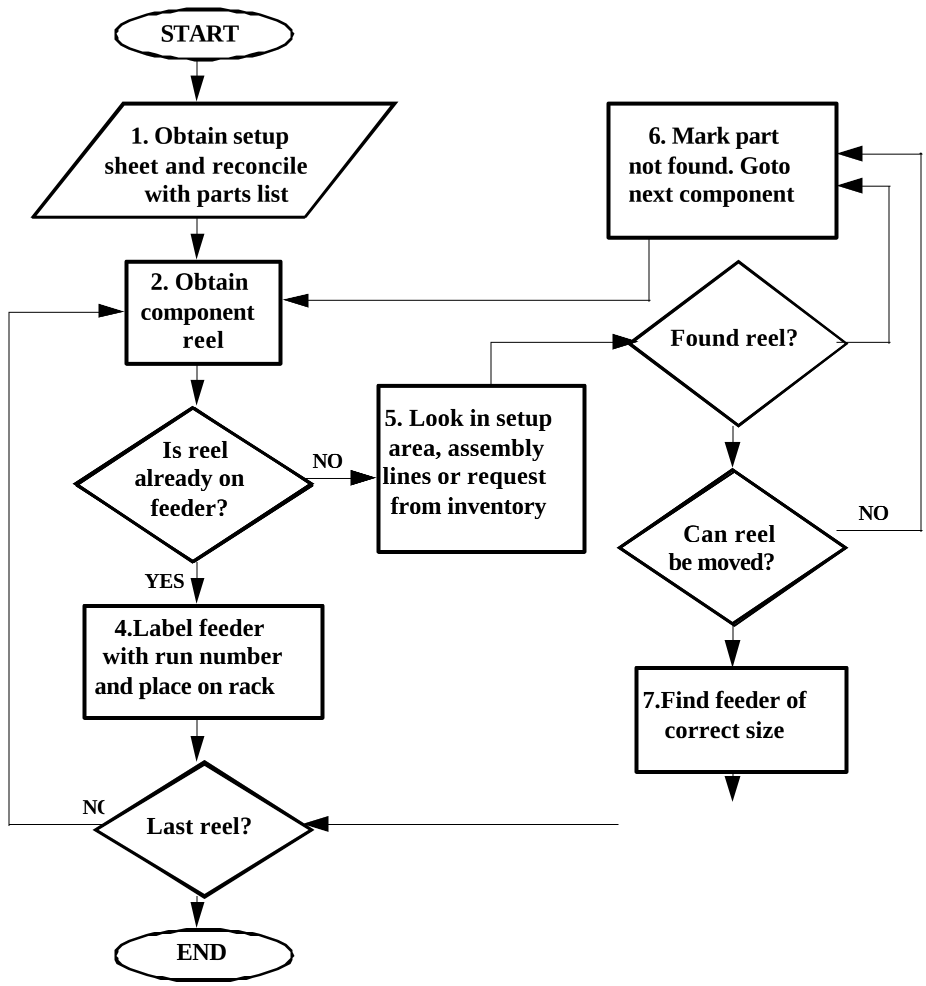

Figure 1 Feeder Setup Process Flow Diagram

Figure 1 depicts the process flow. In Task 1, the setup operator reconciles the parts list for the PCB being assembled, with the setup sheets for the individual placement machines. Once these are reconciled, the operator begins physically locating and collecting the component part reels needed for the setup. Each reel contains one component type that is designated by a part number. Some reels may already be loaded on feeders while others are not. A reel not already on a feeder must be loaded on a feeder of the correct size. There are 27 possible feeder configurations to select from. Component reels may be found in several places: in the raw reel inventory, already loaded on a feeder in the feeder setup area, or on one of the four assembly lines where the feeders may be in use in a current build or part of a build that has just ended. Once the reel is located and put on a feeder, if necessary, it is labeled and placed on a rack. Finally, the feeder is labeled with the component part number and the machine device location.

This process of looking for the reel, loading it on a feeder and labeling the feeder continues until all of the component reels needed for the setup have been procured. Feeder setups can take from 1 to 14 hours per machine. From the timing studies performed and from operator interviews, we determined that approximately 70% of the labor time spent on feeder setups is incurred during tasks 2 through 5. These tasks fall under the heading of *locating parts*. Locating parts, on component reels, is time consuming because there are about 3000 reels in the plant at one time, with little redundancy, and these reels are spread out over a 40,000 square foot area. Usually, there is only a single reel in the factory containing a particular component part number. Moreover, the component part number is 14 digits in length which adds to the difficulty of locating the reel. As a result, looking for components becomes a task akin to locating needles in a field - it sometimes take hours for one reel.

The completed feeders are placed on a movable rack which will hold all of the component feeders prepared during the setup. Tasks 1 through 8 are performed for each component reel in the setup. Once this off-line setup is complete, the racks (one per machine) are grouped together and labeled with the order number. When the scheduled build date and time arrives, the line operators will collect the racks and take them to their respective machines. It is at this point that the on-line setup process commences.

On-line setup

The on-line placement machine setup process occurs at the placement machines. This process is usually carried out by two or more people who perform the setups for all three machines in the assembly line. The setups for each machine are performed in parallel whenever possible to reduce downtime, which initially ranged from one to four hours per setup, and averaged two hours. Figure 2 and Figure 3 show the placement machine setup process flow diagram.

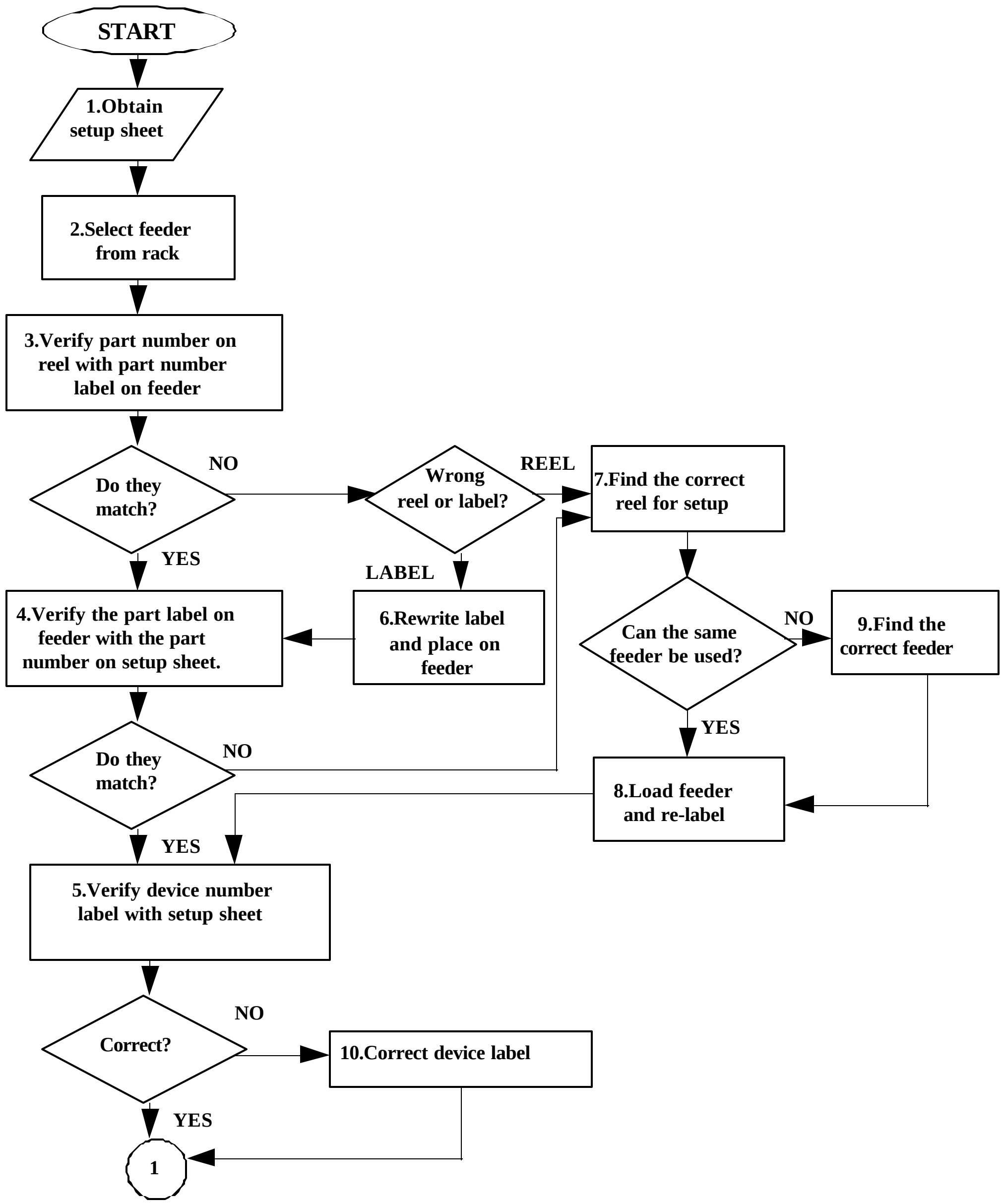

Figure 2 Placement Machine Setup Process Flow (Part 1)

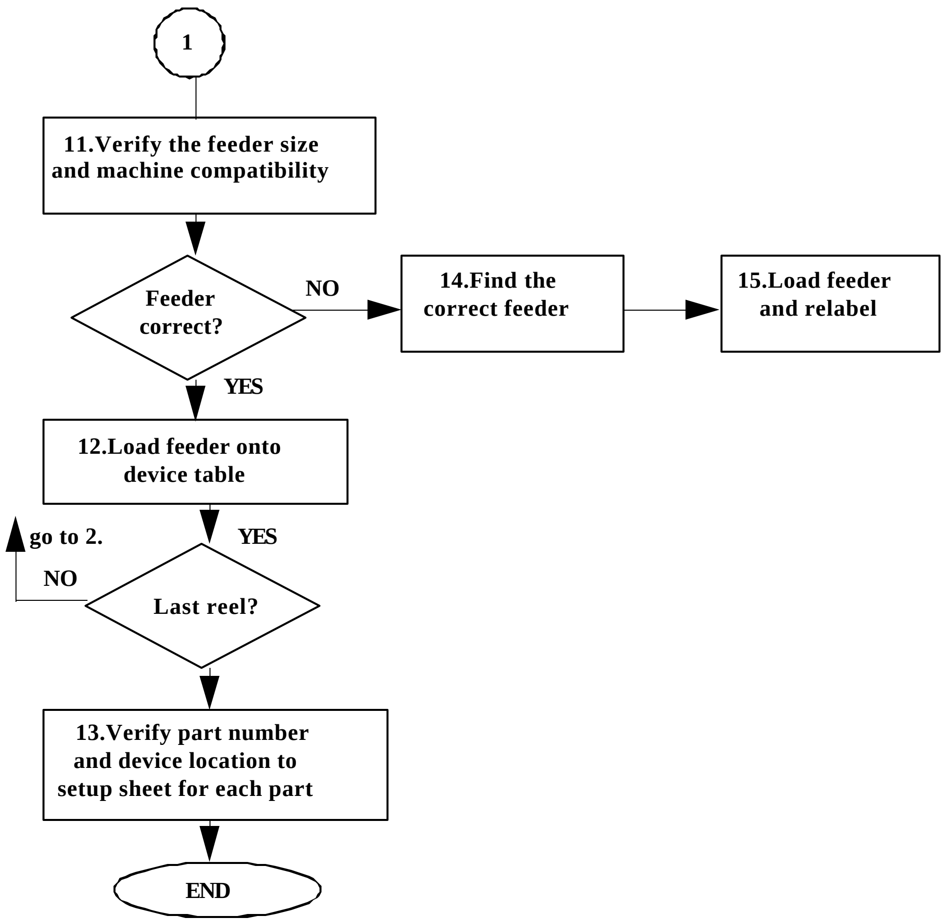

Figure 3 Placement Machine Setup Process Flow (Part 2)

The operator began the process in Figure 2 after he or she obtained the rack of feeders (loaded with component reels). This was usually done right before the machine finished the current production run. Prepositioning tooling and fixtures before the end of the previous run is a standard prescription of SMED. In this case it was already standard procedure even though the setup process had never been formally analyzed.

In tasks 2 through 5, the operator selected the first feeder from the rack and checks that the component in the feeder is the correct component, that the feeder is the correct size, and that the device location called out for this component is correct. The operator then placed the feeder in the designated device location on the placement machine (task 12).

Once finished with a feeder, the operator returned to task 2 to repeat this process until all feeders were loaded on the machine. Once all feeders were loaded, the setup was rechecked to ensure that each component was placed in the proper device location on the machine (task 13). This task was called setup verification and consumed approximately 50% of the total placement machine setup time. Generally the buddy system was employed in this task. One operator read the part number and its device location while another verified the numbers with the setup sheet. For a 50 feeder setup, this task took about 30 minutes.

Setup verification is performed to ensure that the setup is correct, since errors are costly. If the wrong component is placed and the vision system of the machine does not detect the error, the boards will be populated with the wrong part. Placing unwanted parts results in costly rework and scrap, since the boards must be retrofitted with the correct part once the error is discovered. Usually, errors of this nature are not discovered until they are tested, which results in a need to rework all the boards in the batch. Because of this high penalty for incorrect setups, much time was spent verifying and re-verifying components before the production run.

Managing Complexity

Both the off-line setup (locating and matching reels and feeders) and on-line setup (mounting feeders on the machines) took many hours, and major resources went into the setups. The basic reason was high product variety and the resulting complexity that needed to be managed. The variety arose from the need to make prototype boards, as well as production boards for several business units.

Both parts of the setup were driven mainly by the number of different components, and therefore number of feeders, needed for the board being assembled. Thus the setup durations are a function of board complexity. The situation is exacerbated by the overall complexity of the factory, which increases the amount of effort needed simply to “keep track of” all the elements of setups (reels, feeders, racks, etc.)

Table 1 summarizes the elements which contributed to setup complexity. The factory had simplified the situation by concentrating on only two types of placement machines, but the goal of producing both prototypes and production boards for a number of products had kept everything else complicated.

Table 1 Principal causes of setup complexity

Cause of complexity	Number of types	Absolute number in factory
Reels/part types	3000	4000 (approx.)
Feeders	29 (excl. tray feeders)	3500
Feeders per setup	50 to 300+, 180 avg.	not applicable
Placement machines	2 (high speed+ fine pitch)	12
Boards	>800	

Section 3 Applying SMED to PCB Assembly Setups

In this research, SMED concepts were applied to placement machine setups with promising results. The first phase in setup reduction was to apply SMED concepts to the process.

Figure 2 and Figure 3 outline the machine setup process at the start of this research. The first phase in the SMED methodology is to classify each setup task as either internal or external. On examination of tasks 3-5 in Figure 2 and task 11 in Figure 3, all of them involve verifying information, and none requires interaction with the machine. These tasks could be performed off-line from the placement machine and should be handled as external tasks. Moreover, most of these tasks were already being performed during the external feeder setup process. Requiring the machine operator to re-verify them was a duplication of effort. These tasks were therefore removed from the placement setup process and shifted upstream to the external feeder setup process. Shifting these tasks also shifted the associated error handling tasks (6-10) off-line.

The remaining tasks are inherently internal operations since the machine must be stopped while they are performed. Loading the feeder on the device table and locking it into place (task 12) is an internal operation. Verifying that the setup is correct once all the feeders have been loaded onto the device table (task 13) is an internal operation since it involves verification of components as actually loaded on the machine.

Figure 4 shows the new internal process. This process represents a 50% reduction in the number of tasks performed on-line to the machine, assuming that there are no errors, and a bigger reduction if there are errors, since error handling is now off-line.

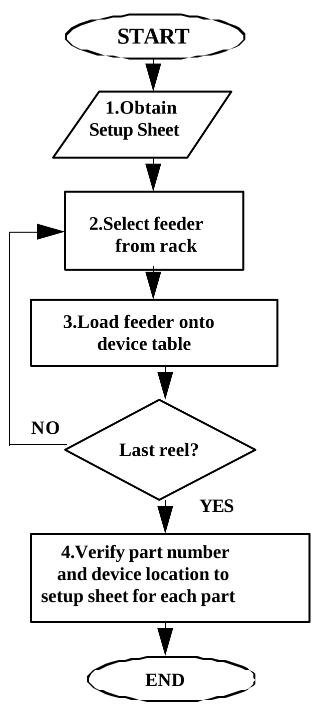

Figure 4 The Modified Placement Machine On-line Setup Process

The second phase in the SMED process is to streamline the remaining internal tasks. Once all of the external operations were moved off-line, only four internal tasks remained. These were: obtaining the setup sheet, selecting a feeder from a rack, loading the feeder onto the device table, and verifying that the feeder was placed in the proper location. Since these tasks were already being done in a fairly efficient manner, there did not appear to be any large improvements to be gained without adding new tools or methods.

Of the four remaining internal tasks, the task taking the greatest amount of time was the verification task. This task (Figure 3, task 13 and Figure 4, task 4) requires the verification of all feeders and their components to the setup sheet after they have been placed on the machine. For this task, the operator (or, sometimes two operators) verifies the component part number for each device location against the setup sheet. This was time consuming and prone to errors, due to the length of the part numbers (14 digits) and the large number of components to verify. Errors result from part numbers being misread and from feeders being switched. Consequently, this task was the focus of further setup time reduction efforts. This was done by creating a new system for feeder management, discussed in Section 4 . The new system also has major benefits for external setup.

Hot swapping

The ideal limit of SMED is to have instantaneous setups. In some cases, the new methods approached this ideal by allowing “hot swapping”. The hot swapping concept takes advantage of the design of the Fuji CP6 high-speed placement machines. Each CP6 machine has two device tables, each holding up to 70 feeders, in order to allow more complex boards to be made. Since there are two CP6 machines per line, this gives a maximum of 280 different feeders (plus about 30 more on the fine pitch machines) per board. However, many PCB designs require 140 or fewer components. For those products, the process engineers who program the machines can reprogram feeder locations to leave one device table entirely empty.

The CP6 machines are designed so that if a device table is not being used, the operator can safely set it up even if the machine is running. In this way, the next job can be fully setup on one device table while the current job is running on the other device table. Thus the placement setup occurs entirely off-line. When the old job completes, the other placement table and job are "hot swapped" by software, with no physical intervention.

There are a number of qualifications which prevent this technique from being used for all boards.

- The currently running product must have fewer than 140 components for the CP6 machines (One device table on each CP6 machine).
- So must the next job.
- Both products must have been reprogrammed by process engineers to have all feeders on a single table. This contrasts to what a board sequence optimization program would do. In sequence optimization, the goal is to leave as many feeders untouched from job to job as possible
- The run length of the first job must be long enough to complete the setup of the device table for the next one. Thus the shorter the on-line setup time, the more effective is hot swapping. If the next setup takes longer than a run, then at the margin downtime is still determined by on-line setup.

- The stencil print, conveyors, and fine pitch machines cannot be hot swapped, which prevents instantaneous setup of the whole line even in the ideal case.

Clearly, hot swapping further reduces line downtime. It tends to shift the bottleneck in setups away from the high-speed placement machines, and toward overall operator time (both on-line and off-line).

Section 4 The Feeder-Management System

Since managing the variety of reels and feeders was time consuming and error-prone, the plant developed a custom information management system to improve it. This required modern technology well outside the range of traditional SMED. The new feeder-management system is a computer-based system that uses bar-code technology, wireless portable data terminals, and personal computers to manage information about the feeders.

The objectives of the Feeder Management System are to:

1. Decrease on-line and off-line setup times
2. Reduce the time needed to physically locate component reels
3. Reduce the time needed to physically locate feeders
4. Automate verification tasks to reduce errors
5. Provide feeder size information
6. Clearly label feeders with size and machine information to reduce feeder selection errors

For example, there is a "Locate Parts" program which allows an operator to find a component reel by simply entering the component part number. The program returns the location of the component reel in the factory. Formerly, the "locate parts" task required the operator to physically go hunting for the desired part.

The information system is designed in a modular fashion. Each software “tool” corresponds to a task performed by an operator prior to the system’s development. The advantage of this modularity was that it was easier to train operators on the system because the software tools related directly to tasks they were already performing manually.

Objective 6 (clearly label feeders with size and machine information to reduce feeder selection errors) was the only one that did not require a computer system. It uses color-coded labels that uniquely identify the feeder size and machine type. The setup sheets now include information about what color of feeder label to look for with each reel, making matches easy.

Architectural overview

Figure 5 depicts the basic design of the system. There are two computer platforms: radio-frequency (RF) portable data terminals running UNIX through a Telnet session and PCs running Windows. Setup personnel use these computers during on-line and off-line setups. Off-line feeder setup personnel use the Feeder Management System software running on a PC to perform feeder setups. On-line setup personnel use wireless terminals.

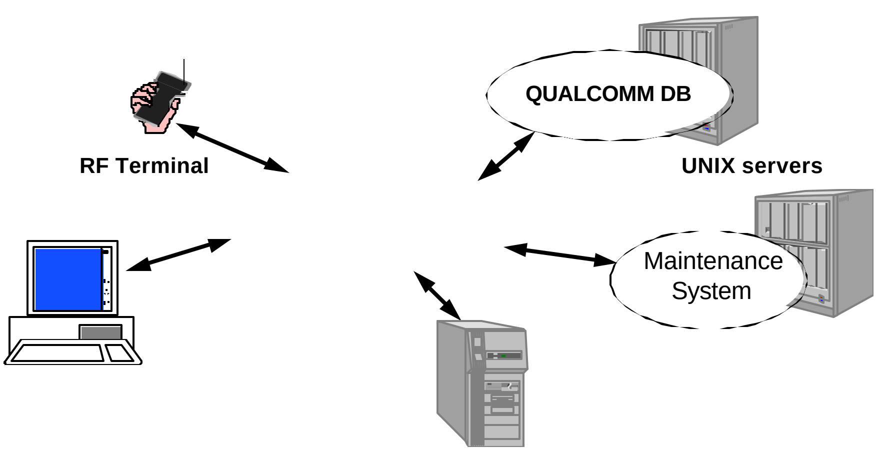

Figure 5 The Hardware Design of the System

For details of the hardware, software, and operation, see Coble (1996). We explain one procedure, the setup verify which checks that the correct reels and feeders have been loaded in the correct slots on the device table. Previously this was done by manually checking the loaded components against the setup sheet. In the new systems it is done with the wireless terminals which have attached barcode wands. Barcode IDs on each feeder are read in sequence. The software on the setup PC automatically checks the feeder ID to determine the component ID in that feeder, and checks the component against the placement list. In this way, the tool verifies that the plan matches what is physically in the device table. If there is a discrepancy, the system provides corrective information. The feeder and reel barcodes are also used for other purposes in the system. We considered the use of RF ID tags, but chose barcodes because of the need to uniquely distinguish one reel or feeder from another one, centimeters apart. RF IDs are not well suited to this task.

Section 5 Results

Overall setup changes included:

- SMED (Single Minute Exchange of Dies) changes, including hot swapping.
- Computerized feeder management system.
- Addition of a third operator to most lines and shifts.

The changes can interact. For example the third operator has less effect on setup times when they have been reduced using the other methods. These interactions will become clearer below.

The effects of these changes fall into four categories. The magnitude and economic value of some of these effects are hard to measure, but they are all potentially significant.

- Reduced line downtime.

- Reduced labor content and elapsed time in both on-line and off-line (feeder preparation) setup. This reduces labor cost and increases production flexibility.
- Reduced errors from incorrect components, requiring less rework. The plant did not keep systematic data on magnitude and causes of rework, perhaps due to political sensitivity of the issue. While we believe the incidence of these problems has gone down due to the easier setup verification provided by the computerized feeder management system, we have no measure of this benefit.
- Miscellaneous benefits, many unanticipated. Unscheduled downtime fell. The system is being used in ways for which it was not designed. For example, it now takes less than five minutes to reconcile the bill of materials to the placement machine program and find discrepant part numbers. As a result this is being done well in advance, and when problems are found they no longer disrupt the actual parts preparation operation. We have only anecdotal information on the size of these benefits.

The rest of this section examines the first two of these effects, and discusses implementation issues and next steps.

Placement machine on-line setups

Operators and one of the authors conducted time studies on the setup of individual high-speed placement machines by a lone operator, using a sample of jobs of different sizes. The average setup required 31 minutes using the new methods, with a standard deviation of 8 minutes. This is the internal time to set up a single high-speed machine by a single operator. By comparison, nine setups of various sizes measured before any changes averaged 78 minutes, with a standard deviation of 33 minutes.

To more precisely compare the speeds of the old and new methods as a function of setup size, we ran regression analyses for each (Table 2). All coefficients are statistically significant at the 5% level.

Table 2 New and Old Setup Times: Regression Results

Setup time in minutes (new method)	=	18	+	.18 x number of feeders
(standard errors)		(4.1)		(.07)
Adjusted R^2 = .48		Standard error of residuals = 2.7 minutes		
Estimated time for 50 feeder setup = 27 minutes				
Setup time in minutes (old method)	=	45	+	1.67 x number of feeders
(standard errors)		(15)		(.61)
Adjusted R^2 = .45		Standard error of residuals = 24 minutes		
Estimated time for 50 feeder setup = 128 minutes				

The regression shows not only that total times differ, but also that the new method removes most of the dependence on setup size. The incremental time per feeder (and per part) goes down by almost an order of magnitude. Presumably this is due to the high speed with which feeder barcodes can be scanned in the final verification. The hundred-fold reduction in variance of setup time for the new method is also in its favor, since it makes scheduling easier. The lower variability is due, we believe, to the much smaller number of problems that have to be rectified by setup operators while the machine is stopped.

Economic value of faster setups

Previous studies of setup reduction have not estimated the overall value, perhaps because it depends on the product mix and includes several imponderables. The biggest financial impact of the new setup methods is from reduced downtime for the production lines. The plant ran at a rate of about 1150 setups per year, rising as product variety and prototyping increased. Downtime is valued at $700 per hour, based on the value of capital equipment as well as operator costs.

The actual line downtime per setup depends on the staffing level for setups and the frequency and effectiveness of hot-swapping, as well as on the improvements in setup methods themselves. The plant had recently shifted from two to three operators as the standard staffing level for the lines, partly in order to speed setups.

We can construct several scenarios to estimate the cost of setup downtime before and after the new system (Table 3). Under the conventional setup method, a single machine with 50 feeders took an average of 128 minutes or 2.13 hours. With 2 operators setting up 3 machines this meant the line was down for 3.2 hours. Approximately an additional .5 hours was needed for non-feeder setup activities, including software download, screen print machine, and conveyors, for a total of 3.7 hours. This gives a total of 4255 hours of downtime per year, with an economic value of $3.0 million.

Actual time spent on setups and setup-related disruptions was higher than our 3.7 hour estimate, because of problems such as missing or incorrect parts, waiting for the off-line setup to be completed, machine difficulties, etc. For example if a feeder reel ran out of parts in the middle of a run, the line stopped while the operators located another reel and loaded it. This could take as long as an hour, since the replacement reel could be anywhere. The new system has ameliorated many of these disruptions. Off-line setup personnel locate sufficient reels using the "locate parts" command before the run begins. However we have no good data on reduction of disruptions, and are therefore omitting them from benefit calculations.

Under the new system, suppose for now that hot swapping is not used. With 3 operators per line, one for each placement machine, all three placement machines can be set up in parallel. A conservative assumption is that operators cannot double-team the setups, so that total setup time for the three machines equals the slowest of the three setups. Making various approximations and using the regression analysis in Table 2, if setups average 50 feeders with some variation around this number, the slowest of the three setups will average about 30 minutes. The non-feeder setup activities can be done faster under the new system than before, partly because of the third operator, in roughly 20 minutes elapsed time. Total time is therefore 50 minutes per setup, 960 hours per year, with an economic value of $670,000. This is a 78% reduction, or almost a 5-fold improvement.

Table 3 Economic Value of Reduced Downtime

Case	Setup time per machine (min.)	Elapsed Setup time, 3 machines	Elapsed time, whole line	Hours/yr. for 1150 setups	Cost of time ($000 /yr.)	Reduction (percent of base)
Base case	128	192 min.	222 min.	4200 hrs.	$2,980	----
3 operators; new system; no hot swapping	27	30	50	960	$670	78%
3 operators; new system; 80% of setups are hot swapped		25 when hot swapped	34 = weighted average	652	$456	85%

In fact hot swapping of both high-speed machines can be used in about 80% of the setups. In these cases only the fine-pitch placement machine must be set up off-line. This machine has fewer feeders than the high speed machines, so should average around 25 minutes. Meanwhile the other two operators can be doing the remaining non-feeder activities, so that the total duration is approximately 30 minutes. Taking a weighted average of 30 minute and 50 minutes per setup gives an average of 34 minutes per setup, for a total scheduled downtime of 652 hours per year, with an economic value of $456,000. This is a 7-fold improvement over the base case. (Using two operators instead of three would only add about ten minutes. The main benefit of the third operator is probably faster responses to problems during a run, which we do not evaluate.)

Labor savings

In addition to reducing line downtime for setups, the new methods substantially change the off-line setup activities (while the line is running). One important change is faster work by the off-line setup operators, who use the Bill of Materials to pull the correct reels and feeders for a job, and put them on a rack prior to the setup (See Figure 1). Benchmark studies estimated 4.2 labor hours per job, prior to the changes. About 70 percent of this time was spent looking for parts.

No hard data is available post change, but we estimate a 40 percent reduction in time searching for parts due to use of the feeder management system. This is mainly because the new system accurately locates parts reels about 95 percent of the time, no matter where they are in the factory. Thus the savings is approximately 1350 labor hours per year.

In addition to seven off-line setup operators total, the plant has about 25 material coordinators. They asked to use the feeder management system, and find it makes their jobs easier. Chasing parts used to average an hour per part. With the new system it is down to ten minutes per request. Since about a quarter of their time was devoted to chasing parts, this is a 20 percent improvement in their overall effectiveness for an additional 10,000 labor hours per year.

Offsetting these labor savings are additional off-line activities for line operators, which were previously done while the line was stopped. For these and other reasons, most lines now have three operators rather than two. This works out to about 5 additional operators, offsetting the reduction in setup time by the off-line operators.

We can now summarize the economic benefits of the new setup system (Table 4). This is based on $700 per hour for line downtime, and $40 per hour for operators including supervision, etc. Clearly, the big impact is from reducing line downtime by 3900 hours per year for the whole plant, the equivalent of a fifth line.

Table 4 Summary of Economic Benefits

	Old system	New system	% Change	$ savings/yr. with 1150 setups/yr.
Setup Downtime, elapsed hours/setup	3.7 hours	0.56 hours	-85%	$2,500,000
Off-line setup time, labor hrs./setup	4.2 hours	3.0 hours	-28%	$54,000
Material handlers	25	24 (equiv.)	-20%	$400,000
Line operators per line	2	3	+50%	-$380,000
Total benefit per year				$2,600,000

Development Costs

These setup improvements were developed over the course of more than a year. We estimate the one-time development costs at about $350,000. These break down as follows: hardware including nine wireless terminals $45,000, lead engineer $100,000, other engineers, programmers, and consultants working part time $200,000. Software and database costs were reduced by integrating the feeder management system into existing databases. All labor costs are burdened. With benefits of $2.6 million per year and costs of $350,000, the payback time is .13 years. Using a 20% discount rate, a conservative two year life, and several assumptions about time phasing, these numbers give a net present value of $3.2 million, or nine times the original investment. This is, very roughly, the cost of purchasing an additional assembly line.

Implementation issues

There were a number of implementation issues during the deployment of the system in the factory. First, a number of the operators were not familiar with the personal computer platform and had to be trained in the basics of Windows before training them on the system. Computer training consisted of a two hour hands-on session given by the Qualcomm training department.

Second, it was important to keep the operators informed of the system's progress to maintain enthusiasm for the system. System training consisted of a number of discrete steps occurring over the life of the project. All of the operators, both those involved with the system design and others, were kept informed of the system's progress during its development and of the benefits it was expected to provide. Later, all of the operators were given demonstrations of the system prototype to keep them informed and involved in the process. The system was developed on a single line and deployed to the other lines only when it was debugged. This allowed us to train operators gradually as we moved from one line to the next. System training occurred on the job, which allowed the operators to use the system as it was intended rather than in a simulated environment. Because the operators knew what to expect with the system, they were extremely enthusiastic about it, even when system bugs impeded their progress. The operators were also invaluable in finding system bugs and discrepancies not caught earlier during acceptance testing.

The one-page Quick Start cards created as part of the user training manuals allowed the operators to learn the system tools quickly, from cards, without consulting the user manual.

Finally, the system had to be deployed so as not to disrupt production. This required coordination with the planners, schedulers, and supervisors.

Section 6 Conclusion

In Ohno's terminology about setups, "single minute" exchange of dies refers to single digit setups, i.e. less than 10 minutes. Since he typically worked with stamping presses with multi-hour setups, this was a major accomplishment.

The approach to setup reduction described here started with traditional SMED re-engineering. By applying the principles of SMED to pick and place chip shooter machines, we were able to reduce setup times by removing all activities that could be done off-line. The key task of verifying feeders, however, must be done on the actual feeder tables, and was time consuming and error prone. Therefore we built a computerized information system to assist with feeder management. For speed and operator convenience, it uses a modern panoply of computerized tools, e.g. barcode readers and wireless terminals.

The net effect of these changes was to reduce the incremental setup time per feeder from 1.7 minutes to .18 minutes or 11 seconds (based on regression results in Table 2), a 9-fold improvement and approaching "single second." The total time to do a standard 50 feeder setup is still about 30 minutes. We estimate the average improvement in total line setup time to be about 84% from 3.7 hours to less than 0.6 hours. From our cost and benefit calculations, we estimate an NPV/cost ratio of 9:1, and a payback period of less than two months. We view these results as support for the hypothesis that taking a "dynamic approach" to production, i.e. improving the core production processes by deliberate improvement efforts, can have very high payoffs (Jaikumar and Bohn, 1992).

It is useful to compare our results with other efforts to improve setup times, but published data is scanty. Aguayo and Tran (1994) report "30 seconds per feeder" for setups after implementing their verification system. Jain, et al (1996) report one to five minutes per feeder at various H-P plants to set up similar chip shooter machines. They used an optimization approach which changed the sequence of jobs. Their best implementation of their method gave a 70-80 percent reduction in setup times of the chip-shooter but with some increase in run time. Another implementation gave a theoretical reduction of 53 percent and a documented 31 percent decrease in setup times. None of these authors discuss the time for setting up the whole line, nor the economic value.

This project demonstrates the applicability of Ohno's Single Minute Exchange of Dies approach well beyond the industries where he developed it. His fundamental insight of separating internal and external setup activities proved its value. Another insight in his work is that simple methods are usually sufficient, and where possible we used his "common-sense" techniques, such as color coding the different sizes of feeders and reels to make them easy to match. However our factory had 4500 different reels and 3000 different part numbers. Operators could not keep track of such a large number of items effectively using simple methods; therefore it was necessary to add a state-of-the-art computer system for keeping track of the reels and feeders. We believe that the simple (SMED) and sophisticated (computer) methods were complements. Either alone would not have been nearly as effective. Optimal sequencing of jobs could provide further benefit, but since printed circuit board assembly is only the first step in producing a final product in a tightly coupled factory, it would require an elaborate modeling effort.

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