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Setup Time Reduction for Electronics Assembly: Combining Simple (SMED) and IT-Based Methods

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As much as 50% of effective capacity can be lost to setups in printed circuit board assembly. Shigeo Shingo showed that radical reductions in setup times are possible in metal fabrication using an approach he called "Single Minute Exchange of Dies" (SMED). We applied SMED to setups of high speed circuit board assembly tools. Its key concepts were valid in this very different industry, but while SMED typically emphasizes process simplification, we had to add modern information technology tools including wireless terminals, barcodes, and a relational database. These tools shield operators from the inherent complexity of managing thousands of unique parts and feeders.

The economic value of setup reduction is rarely calculated. We estimate a reduction of key setup times by more than 80%, and direct benefits of $1.8 million per year. Total cost of the changes was approximately $350,000.

Key words: setup reduction; printed circuit board assembly; SMED; flexibility; process improvement
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1. Introduction

This paper examines setup time reduction for printed circuit board assembly (PCBA) in the electronics industry. PCBAs are a basic building block of electronics and are found in virtually every electrical product. Setups are vital because they have major impacts on downtime, capacity, quality, and costs. Errors in setups lead to incorrect assembly, requiring manual diagnosis, and rework.

We used a rapidly growing PCBA 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 first developed for metal fabrication processes (Shingo 1985). The second part developed a sophisticated factory information system, with hand-held wireless barcode computers, to further reduce setup times and increase setup accuracy. The net result was an 80% 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. Section 2 describes the technology of printed circuit board assembly. Section 3 describes how SMED concepts can be applied to these setups. Section 4 introduces the computerized information system. In Section 5, we investigate the effects and economic cost-benefit of the improvements. Section 6 discusses conclusions.

Setups are inevitable whenever a manufacturing process makes more than a single product, but they are undesirable because they take time away from production. In printed circuit board assembly, setups can consume as much as 50% of total operating time (Sadiq and Landers 1991). Manufacturers traditionally used long production runs and the accompanying large lot sizes in order to reduce the number of setups needed. But large lots sizes create numerous problems, including high work-in-process and finished goods inventories, longer lead times, and slower information flows. Infrequent runs of each product require carrying higher safety stocks, making it difficult to respond to demand shifts or product revisions, and generally making production inflexible.

Just-in-time (JIT) production emerged as an alternative to the traditional large-lot approach. It requires frequent production of small quantities only when they are actually needed. But JIT production requires frequent small batches, with quick shifts from job to job as diverse parts and subassemblies are "pulled" through the factory. This can only be done with short setups, so that setups do not eat too far into run time and capacity (Cavinato 1991; Fiedler et al. 1993; Hall 1983; Hay 1989; Mirza and Malstrom 1994). 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. Consistent with Economic Order Quantity formulas for determining lot sizes, production schedulers and planners frequently cite setup costs as a major factor in setting lot sizes. This was observed at our site and was also reported by Ammons et al. (1992).

Faster setups confer numerous benefits beyond smaller lot sizes, including lower labor costs, higher effective capacity, and more flexibility, all of which are critical for response to market forces such as rising product variety and customization (Davidow and Malone 1992). Bradley and Conway (2003) show that a reduction in setup time will result in lower cyclic inventories. Esrock (1985) gives an exhaustive list of the positive effects of setup time reduction on manufacturing operations. Setup time is an important parameter in shop-floor scheduling problems, especially in models that include lot sizing decisions. Examples include Bradley and Conway (2003), Chiu, Chen, and Weng (2003), Kim and Bobrowski (1995), and Kreipl and Pinedo (2005).

Various authors have formally modeled the value of investing 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. Hahn, Bragg, and Shin (1988) examine the operating characteristics of setup when used as a decision variable in a capacity-constrained environment. They demonstrate 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. Kim, Hayya, and Hong (1995) model the effective capacity increase from setup reduction. Leschke and Weiss (1997) examine which product setups to improve first, when improvements are product-specific. Li, Erlebacher, and Kropp (1997) examine setup reduction compared with other methods for reducing the probability of stockouts when demand is stochastic.

1.1. Setup Reduction by Single Minute Exchange of Dies

Environmental changes such as increasing product variety and use of JIT have raised the value of fast setups. In response, systematic methods have been developed for improving setups. At least two independent approaches are in use. One originated in Japan and emphasizes shop floor issues, with no use of information technology. It was originally developed for fabrication processes such as auto parts stamping, and has been applied mainly in "low tech" industries. The other approach is used for electronics assembly especially PCBAs, and uses computers running sophisticated mathematical optimization algorithms.

Shigeo Shingo (1985) developed the more general approach, which he called SMED: Single Minute Exchange of Dies. SMED is a methodology for systematically re-engineering setup processes, and thereby radically reducing their duration, with documented reductions from hours to less than 10 minutes ("single [digit] minutes").

The SMED methodology consists of three phases. In the first phase, setup tasks are differentiated based on whether they can be performed while the machine is running (external tasks) or must be performed while the machine is stopped (internal tasks). For example, when examining the setups for the large body molding presses at Mazda, Shingo (1985) discovered that the presses were shut down while mounting bolts for the new die were being located. Once a setup process is analyzed in this way, it is possible to reschedule many tasks as external activities that are performed while the machine is operating. An example is prepositioning all dies and tools needed for the next setup while the previous job is still running. Only the remaining internal tasks require the machine to be stopped.

In the second phase, technical modifications enable some of the remaining internal tasks to be done externally (Van Goubergen and Van Landeghem 2001). Modifications can include changes to the design of machines, processes, and even products, but these changes are usually small, inexpensive, and highly targeted (Mileham et al. 1999; Van Goubergen and Van Landeghem 2002).

In the final phase of SMED, all tasks of the machine setup, both internal and external, are streamlined to make them faster and more (labor) efficient. Internal setup improvements give labor savings and less machine downtime. External task improvement does not directly improve downtime, but frees operators for other activities, as we will demonstrate. The methods used for streamlining include industrial engineering and process re-engineering: look at all the activities that go on, omit the non-essential, and design faster ways to do the essential. Typical changes include replacing general tooling, fixtures, and adjustment mechanisms with customized equivalents that require little or no adjustment; 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 preloading raw materials for the next batch. Where possible, "foolproofing" is used to prevent errors, to make them obvious when they occur, or to reduce their effects (Nakajo and Kume 1985).

A variety of good practice-oriented material has been written about SMED in different industries, such as Sekine and Arai (1992), and Mileham et al. (1999). 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. Van Goubergen and Van Landeghem (2002) generalize a list of "design rules" from 60 projects. The unit of analysis in these studies is almost always a single machine setup—the wider impacts of the speedup are not examined. Leschke (1996) presents five brief organizational case studies of setup reduction, and discuss common patterns in the way different reduction activities are sequenced.

1.2. Setup in PCBA

Although SMED has been applied in a wide variety of industries and processes, there are very few documented applications in high-tech processes, including PCB assembly. Nonetheless, there is significant literature on speeding setups in PCBA, but using computer-intensive methods that are completely distinct from SMED. (The only exception is Sharma (2001), which briefly discusses SMED in PCBA.) This literature looks almost exclusively at the component placement machines which put small electronic components onto boards. Different board types use different components, and all the components needed for the next job must be loaded during a setup. A typical facility has multiple lines and multiple jobs. The resulting operating policies can be formulated as the solution of a set of hierarchical problems for optimizing setup time and total time (Smed et al. 2000).

Speeding setups of these machines can be done by sequencing jobs in a manner that increases the number of components used in consecutive jobs, which reduces the number of changes from job to job. A good introduction is Jain et al. (1996), which combines a discussion of optimization algorithms with results of applications in several Hewlett-Packard plants. Interestingly, they report that setup "time per feeder" ranges from 1 to 5 minutes, but like other authors they treat these times as unchangeable. 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 and Peters 1998; Li and Randhawa 2002; Jin et al. 2002). This literature requires heavy use of information technology, especially the ability to solve large integer programming problems. These optimizations are meant to be used by production planners and machine programmers and are invisible to line operators.

In this paper, we improved setups through a different strategy, namely reducing the *time per component change* rather than the *number* of component changes. As we will show, in some situations this is best done by *increasing* the number of component changes from job to job. We also made heavy use of information technology, but we use it mainly to keep track of complexity rather than attempting to optimize complexity. Another difference is that our system is used by operators, not staff.

A final gap in the literature on setup reduction which we address is analysis of the economic benefits and costs. Speeding the setup of a single machine will be more or less useful depending on how it influences total line downtime. Setup reduction projects, whether by SMED or optimization methods, require investments which can also be measured.

2. Description of Board Manufacturing and Setup

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

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 10 million dollars of equipment, directly support PCBA.

2.1. Process Overview

The total manufacturing process consists of four steps separated by buffers. Testing and inspection are performed at various intermediate points.

2.1.1. Automated Assembly of PCBAs. Printed circuit boards are printed with solder paste, populated with surface mount electronic components, and heated to melt the solder. This process uses highly automated machines and methods typical of the electronics sector, and is the focus of this paper. It is described in more detail below.

2.1.2. Manual Assembly of Through-Hole Components. Most boards have a small number of through-hole components, an older type of electronics package still used for very large or odd components. These components are inserted into the board by hand, soldered, tested, and reworked as necessary.

2.1.3. System Assembly. Tested boards are assembled into functional boxes. Each box contains a number of different boards.

2.1.4. 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 PCBA lines, most of which ran two shifts per day, five days a week.

Because the surface mount portion of the PCBA process is the most capital intensive and has the longest setups, it was viewed as key for setup reduction. The process starts with bare printed circuit boards. Each board is first printed with solder paste, using a precise stencil to control paste placement. The board is then populated with surface mount components, using high-speed automatic placement machines. A typical board contains 1,000 components of about 100 types. On each line, two high-speed placement machines are used to populate the boards with small components such as resistors, capacitors, inductors, and small integrated circuits. Each machine can place up to 28,000 parts per hour. Then, a slower, but finer pitch placement machine is used to place larger components such as Quad Packs and plastic leaded chip carriers.

Once the boards are populated with surface mount components, they are visually inspected, and conveyed into a reflow oven where the boards are heated to melt the solder. These steps are all in-line, hence, must be set up together. Boards then go to manual through-hole assembly, followed by PCBA testing.

Setting up the surface mount assembly process involves preparing the machines and the conveyors between them to the requirements of the board type of the next job. Boards differ in their physical dimensions, solder reflow requirements, and especially the identity and locations of components. Of all the setup tasks, the preparation of the placement machines with their component feeders is the most time consuming. These machines require two labor and time intensive processes: setting up component feeders, and loading the feeders onto the machines. *Feeder setup* involves locating the component types needed for the job, and loading them onto custom feeders. This process occurs away from the machines. The second process is *placement machine setup* in which feeders are mated to the machines. In the terminology of SMED, feeder setup is an external activity, at least potentially, as it does not require the machines to be stopped. Placement machine setup is internal, as the entire line must be stopped while it is going on.

2.2. Feeder Setup

Many hours were spent observing and interviewing the feeder setup and placement machine operators to map out the tasks performed in each process. Feeder-related setup involves gathering components and putting them on feeders. The surface mount components are preloaded on component reels by the vendor. They look very similar to movie reels. Reels come in two diameters and several widths, and may contain as many as 10,000 components each. Before they can be used, the reels must be loaded onto special feeders, which are designed to fit into the specific model of placement machine. Thus feeder setups involve finding the correct reels for a job, mounting them on the correct feeders, and pre-positioning them on racks near the placement machines. The time needed for feeder setups is not fully predictable and feeder setup is therefore usually done several days before a job runs.

The original feeder setup process involves a series of tasks, repeated for each component/reel/feeder combination. First, the feeder setup operators reconcile the parts list for the PCBA being assembled with the job setup instructions ("setup sheets") for the individual placement machines. Next, they physically locate and collect the component part reels needed for the job. Each reel contains one component type that is designated by a part number. Component reels may be found in several places, including the raw reel inventory, already loaded on a feeder in the feeder setup area, or on one of the placement machines. Reels not already on a feeder must be loaded on the correct feeder. There are 29 possible feeder configurations to select from. Once the reel is located and put on a feeder, 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 is repeated for each of the components needed for the job. (For more details, see Coble 1996.)

Before improvements, setting up feeders for one machine took from 1 to 14 labor hours. We determined that approximately 70% of this time was incurred to locate the component reels. This was time consuming because there are about 4,000 reels in the plant at one time, and they are spread out over a 40,000 square foot area. There is little redundancy, so usually only a single reel in the factory contains a particular component. The reels look very similar, so looking for components was akin to locating specific straws in a hayfield.

The loaded feeders are placed on a movable rack which holds all of the feeders required for a machine. Once all of the component/feeders are processed, the racks (one per machine) are grouped together and labeled with the job number. When the scheduled job date and time arrives, the line operators collect the racks and take them to their respective machines. At this point placement machine setup begins.

2.3. Placement Machine Setup

Although beginning a new job requires adjustments all the way down the PCBA line, the setup of the placement machines is the most time consuming, complicated and labor intensive. It is usually done by several machine operators who do the setups for all three placement machines in the line, in parallel whenever possible. The whole line is stopped until it is complete. Figure 1 and Figure 2 show the placement machine setup process flow. F1-2

The machine operator began the process in Figure 1 after he or she obtained the rack of feeders from the feeder setup area, each loaded with its component reel. This was usually done right before the machine finished the previous job. Prepositioning tooling and fixtures before the end of the previous run is a standard prescription of SMED. In this case, it was already the procedure even though the setup process had never been formally analyzed.

In tasks 2 through 11, the operator selected a feeder from the rack and checked that the component in the feeder is correct, that the feeder is the correct size, that

Figure 1 **Original Placement Machine Setup Process Flow (Part 1).**

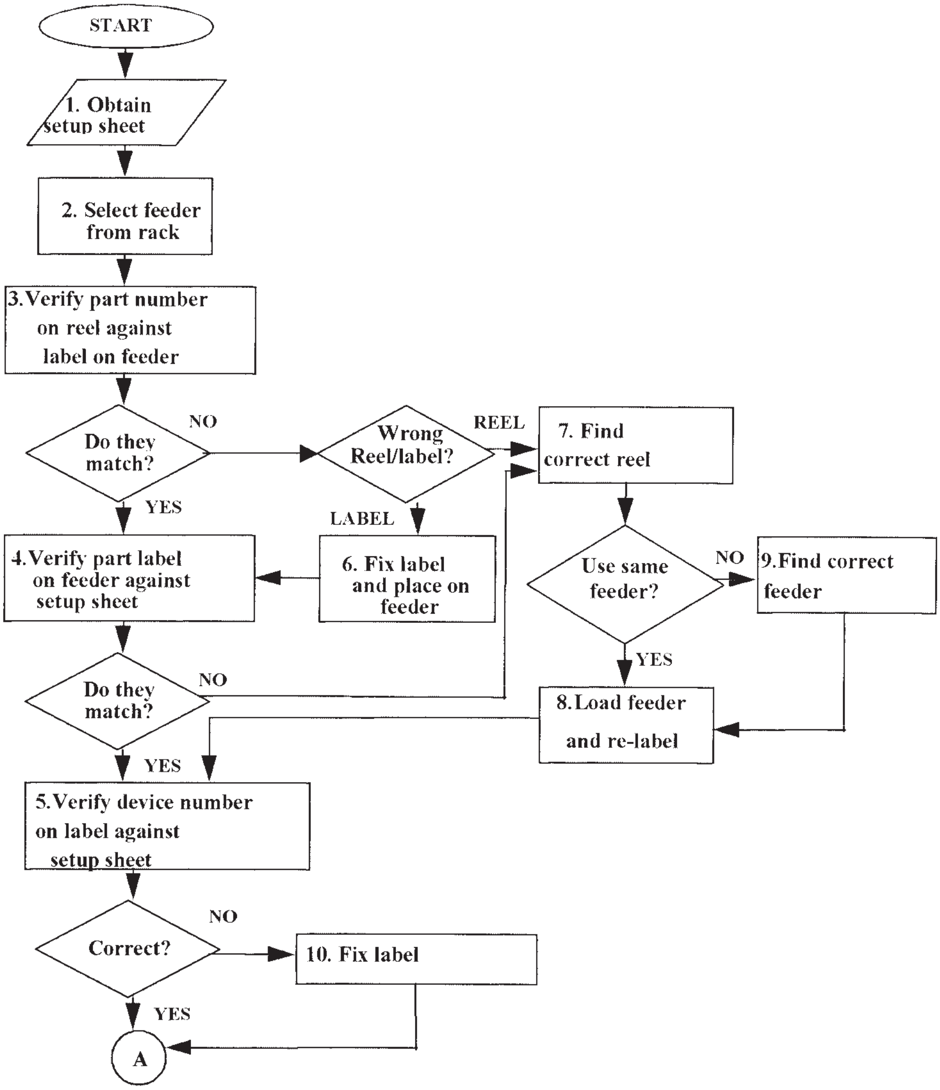
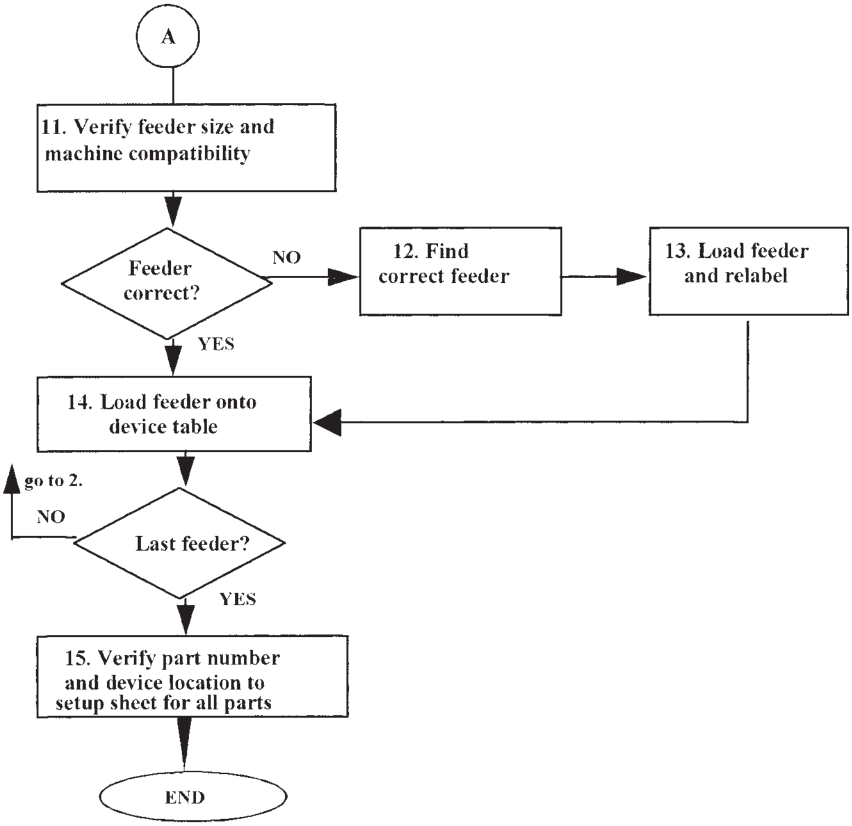


Figure 2 Original Placement Machine Setup Process Flow (Part 2).



the feeder is the correct type for the machine, 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 14).

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 15). This task is 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 against 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 machine's automatic vision system does not detect the error, all boards will be populated with the wrong part. The boards must be retrofit with the correct part once the error is discovered, which incurs several costs including scrap losses and labor. Usually, errors of this nature are not discovered until the boards are tested after manual assembly, which results in a need to rework all the boards in the job. Because of this high penalty for incorrect setups, much time was spent verifying and re-verifying components before the production run. The setup process in figures 1 and 2 was repeated for all three placement machines on the line.

2.4. Managing Complexity in Setups

Both the internal and external setups took many hours, and major resources went into them. The basic reason was high product variety and associated complexity. The variety arose from the product mix for several business units, and the need to make both prototype and production boards. The complexity arose from the number of different boards, plus the high sophistication, and hence, many components of individual boards.

The difficulty of both parts of the setup was driven mainly by the number of different components, and therefore number of feeders, needed for the particular board. 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 difficulty. The factory had two generations and three specific types of high-speed placement ma- T1

Table 1 Principal Causes of Setup Complexity

Cause of Complexity	Number of Unique Types	Absolute Number in Factory
Reels/part types	3000	4000 (approximate)
Feeders	29 (excluding tray feeders)	3500
Feeders per setup	50 to 300+, 180 avg.	not applicable
Placement machines	4 (3 high-speed + 1 fine pitch)	12 (3 machines × 4 lines)
Boards	>800	Unknown
Lines	3	4

chines, plus fine pitch machines. Two of the lines used the older generation and two used the newer. There were 3,500 feeders in the factory partly because the new placement machines needed special feeders. Any radical improvement in setups had to deal with the high level of complexity.

3. Applying SMED to PCBA Setups

In this research, SMED concepts were applied to setups of the placement machine. The first phase in the SMED methodology is to classify each setup task as one that is truly internal to the setup or can be external: internal meaning that the machine is stopped while it is done, external that the task can be done independently of the machine. Shingo writes, "In traditional setup operations, internal and external setup are confused; what *could* be done externally is done as internal setup, and machines therefore remain idle for extended periods. In planning how to implement SMED, one must study shop floor conditions in great detail" (Shingo 1985, p. 28).

In the original placement machine setup process, all tasks on Figures 1 and 2 were done as internal setup, while the line was down. But only tasks 14 and 15 on Figure 2 actually require interaction with a stopped placement machine (for safety as well as practicality). The other tasks involve handling feeders separately from the machines. Moreover, tasks 3 through 13 duplicated activities that should have been performed during the earlier feeder setup process, or recovered from errors in them. Following SMED principles, tasks 3 through 13 were removed from the machine setup process and shifted upstream to the external feeder setup process. Both the verification steps and the associated error handling were shifted.

For the remaining tasks, the machine must be stopped while they are performed. Once all possible operations were made external, only four internal tasks remained. These were: obtaining the setup sheet (task 1), selecting a feeder from a rack (task 2), loading the feeder onto the device table (task 14), and verifying that all feeders were placed in the proper location (task 15). Of the four, the final setup verification task took the most time, on the order of 30 minutes. For this task, the operators compared the component part number for each 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 resulted from component part numbers being misread and from feeders being loaded in the wrong machine device location. Consequently, this task was the focus of further setup time reduction efforts. This was done by creating a new system for managing feeders, discussed in Section 4. This new system also had major benefits for the external feeder setup process as well.

3.1. Hot Swapping

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

The CP 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 set up on one device table while the current job is running on the other device table. When the old job completes, the other placement table and job are "hot swapped" by software, with no physical intervention. Thus, even tasks 14 and 15 of the placement machine setup can be done entirely externally (while running).

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

- The currently running board must have 140 or fewer components placed by the CP machines.
- So must the next job.
- Both boards must have been reprogrammed by process engineers to have all feeders on a single device table. This is opposite to what an assembly sequence optimization program would do, because in sequence optimization the goal is to leave as many feeders untouched from job to job as possible.
- The run time of the first job should be long enough to complete the setup of the other device table for the next job. If the next setup takes longer than the job, then at the margin downtime is still determined by internal setup.

The solder paste printing machine, conveyors, and fine pitch placement machines cannot be hot swapped, and must be done internally. This prevents instantaneous setup of the whole line even in the ideal case. But clearly, when it is applicable, hot swapping can reduce line downtime. It tends to shift the bottleneck in setups away from the high-speed placement machines, and toward overall operator time (for both internal and external). We quantify these effects in Section 5.

4. The Feeder-Management System

In the SMED methodology, once internal and external tasks have been identified, and as many as possible made external, both internal and external tasks are streamlined. Most of the setup tasks and time revolved around the reels and feeders, whose number and variety made them hard to keep track of and easy to make errors with. Therefore, the plant developed a custom information management system to help manage reels and feeders. The new feeder-management system is a computer-based system that uses barcode technology, wireless portable data terminals, PCs, and relational databases to manage information about the components, reels, and feeders.

The system is designed in a modular fashion. Each software "tool" corresponds to a task performed by an operator under the old system. Modularity made the system easier to develop, and it was easier to train operators on the system because the software tools related directly to tasks they were already performing manually. For example, there is a "Locate Parts" tool which allows an operator to find a component reel by simply entering the component part number. The program returns its location in the factory. Formerly, the "locate parts" task required the operator to physically hunt for the desired reel.

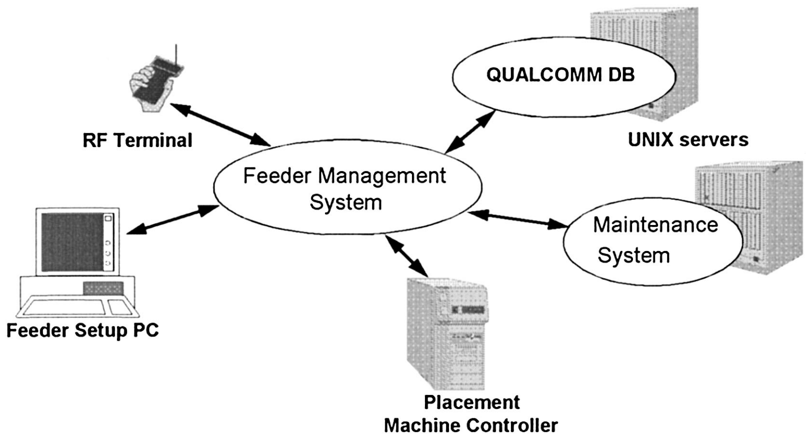
F3 Figure 3 shows the basic architecture of the system. There are two computer platforms: radio-frequency (RF) portable data terminals running UNIX, and PCs running Windows. Setup personnel use these computers during feeder and machine setups. The system is integrated with the appropriate databases on existing factory servers.

For details of the hardware, software, and operation, see Coble (1996). We explain one tool, the *setup verify* which checks that the correct reels and feeders have been loaded in the correct locations on the machine device table (task 15 in Figure 2). Previously, this was done by manually checking the loaded components against the setup sheet, usually with one operator reading aloud to a second one. In the new system, it is done with the wireless terminals which have attached barcode scanners. A single operator scans each feeder barcode on the device table. The software compares the component part number loaded in that feeder against the setup sheet. In this way, the tool verifies that the setup sheet matches what is physically in the device table. If there is a discrepancy, the system provides corrective information. The feeder and reel barcodes are used for multiple other purposes as well. We considered the use of RF ID tags, but chose barcodes because of the need to reliably distinguish one reel or feeder from another, centimeters apart. RF IDs are not well suited to this task.

The Feeder Management System evolved over time. Its ultimate contributions included the following:

1. Decreased internal setup time and thereby reduced downtime.
2. Reduced operator (both feeder setup and machine setup) time needed to physically locate component reels and feeders. The database tracks location of all reels and feeders.
3. Semi-automatic verification tasks to reduce time and errors.
4. Provided feeder size information so operators know what feeder to use.
5. Clearly labeled feeders to make sure operators have selected the appropriate feeder.

Figure 3 Basic Architecture of the Feeder Management System.



Labeling feeders to reduce selection errors was the only improvement that was, in the main, done without computers. Instead, feeders were given color-coded ID labels that identify the 29 feeder types. The machine setup sheets now include information about what color of feeder label to look for with each reel, making matches easy. The rest of the Feeder Management System is based on networked computers and integrated into the rest of the factory IT system.

A standalone system for item 3 above, verification was built by Aguayo and Tran (1994). Their system uses a non-networked PC for each placement machine. The PC activates LEDs on the machine to indicate which feeder slot should be filled next. It also has a sensor in each slot to check that the correct slot was indeed filled.

5. Results

The academic literature on setup reduction is mostly quiet on actual benefits, and even quieter on costs of setup reduction. One reason may be that while is that it is relatively straightforward to predict the narrow technical effect of a change, the benefits depend on interactions among a number of factors and are not a simple function of the technical speedups. For example, radically improving setup of the placement machines can shift the critical path of the overall line setup to total labor time. Also, if proper advantage is taken of reduced setup times, in principle many indirect benefits will ensue. Cavinato (1991) notes that: "The ripple effect [of setup reduction] 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. . . . "

In this section, we estimate the direct technical and economic benefits of the various changes in PCBA. We have only anecdotal information about some of the benefits, such as improved quality. Therefore, we evaluate only two effects: line downtime, and total labor time. Line downtime for internal setups decreased roughly seven-fold as a result of SMED changes, saving approximately $1.8 million per year in direct benefits. Labor time for direct and indirect setup activities also fell, but the net effect was reduced by other changes. We also discuss some implementation costs and difficulties for the new system.

5.1. Internal Setup Results

The effect of the system on internal setup time is an empirical question, and varies from job to job for several reasons. To study it, an experienced industrial engineer conducted time studies over the course of several weeks, using a sample of jobs of different sizes on a single line. In this sample, the average internal setup of a high-speed placement machine required 31 minutes using the new methods, with a standard deviation of 8 minutes. This is the downtime to set up a single high-speed placement machine by a single operator. Nine comparable setups done using the old methods averaged 78 minutes downtime, with a standard deviation of 33 minutes.

Internal setup time depends not only on what method is used, but on how many components must be placed, which varies by job. We used regression analyses to estimate this effect (Table 2). Gathering the data took several weeks, and the sample sizes are smaller than desirable, but the results are all statistically significant by conventional criteria. T2

According to these results, a "standard job" with 50 parts/feeders takes on average only 21% as long, and using the new setup method, 27 minutes instead of 128 minutes. The new method also removes most of the internal dependence on setup size, because tasks 3 through 13 in Figure 1 are now all external, and the single remaining verification task 15 is much faster. The empirical results confirm this: the incremental time per feeder goes down by almost an order of magnitude, to 0.18 minutes or 11 seconds each. The variance of the residual error of setup time falls almost two orders of magnitude, which 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, since most of the checking tasks are now done beforehand. We are not aware of any previous data on variance in PCBA setup times, despite its importance for scheduling.

5.2. Economic Value of Faster Setups

Previous studies of setup reduction have looked only at the technical speedups, as in the calculations above. But what is the economic value of a technical speedup? The biggest financial impact of the new setup methods is from reduced downtime for the production lines. When the system was first implemented, the plant was running at a rate of about 1,150 setups per year, rising as product variety and proto-

Table 2 New and Old Internal Setup Times: Regression Results

Setup time in minutes (New method) =	18 +	.18 × number of feeders
(standard errors)	(4.1)	(.07)
Adjusted R^2 = .48	n = 7	Standard error of residuals = 2.7 minutes
Estimated time for 50 feeder setup = 27 minutes		
Setup time in minutes (Old method) =	45 +	1.67 × number of feeders
(standard errors)	(15)	(.61)
Adjusted R^2 = .45	n = 9	Standard error of residuals = 24 minutes
Estimated time for 50 feeder setup = 128 minutes		

One outlier was dropped. All coefficients statistically significant at the 5% level.

typing increased. Both scheduled and unscheduled downtime are valued at $700 per line-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 most lines, partly in order to speed setups. Because operators can work in parallel on different machines, total line downtime will be much less than the sum of machine downtimes.

We constructed several scenarios to estimate the duration and cost of setup downtime as shown in Table 3. Under the conventional method, the regression results in Table 2 predict that a single high speed placement machine with 50 feeders takes an average of 128 minutes or 2.13 hours to set up. In addition, internal setup includes downloading recipes, adjusting conveyors, and setting up the solder paste plus the fine pitch placement machines. Total time for these activities is roughly one labor hour. We will make the conservative assumption that this time is completely fungible, so that two operators can do it in half an hour.

This brings the total internal setup to 158 minutes, or more than two and a half hours. With 1,150 setups this gives a total of 3,028 hours of setup downtime per year, with an economic value of $2.1 million. This does not include any allowance for problems during or after a run that result from errors in the setup, such as the common problem of loading a reel that runs out of components midway through the run.

What will happen to downtime under the new system? Suppose for now that hot swapping is not used. With 3 operators per line, two operators can set up the high speed machines while the third starts on the other setup tasks. These two will finish in 27 minutes for the same 50 feeder job, and can then join the third operator. The miscellaneous activities will require an additional 11 elapsed minutes, for a total of 38 minutes. Total setup time will therefore be 728 hours per year, with an economic cost of $510,000. This is a 76% reduction from the base case, a four-fold improvement.

Hot swapping of both high-speed machines can be used in about 80% of the setups. In these cases, the three operators will take only 20 minutes to do the miscellaneous activities. Taking a weighted average of 38 minutes and 20 minutes per setup gives 23.6 minutes average, for a total scheduled downtime of 452 hours per year, with an economic value of $317,000. This is a seven-fold improvement over the base case.

5.3. Total Savings

In addition to reducing line downtime for setups, the new methods substantially change the external setup activities (while the line is running). One important change is faster work by the seven external feeder setup operators, who use the job's Bill of Materials to pull the correct reels and feeders for a job, and put them on a rack prior to the setup. 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 conservatively estimate that the feeder management system reduces time searching for parts by 40 percent. 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 1,350 labor hours per year.

The plant also has about 25 material coordinators. They asked to use the feeder management system, and found it made their jobs easier. Chasing parts used to average an hour per part. With the new system, it is down to 10 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 external setup activities for machine 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 worked out to about 7 additional operators.

We summarize the economic benefits of the new

Table 3 **Economic Value of Reduced Downtime**

Case	*S* = Setup time per HS place machine	*T* = Total labor required = 60+2S	Internal setup time = *T*/# ops.	Hours/Year for 1,150 setups	Value @ $700/hour ($000/year)	Reduction (percent of base)
Base case: old method, 2 operators	128 minutes	316 minutes	158 minutes	3028 hours	$2,120	—
New method and 3 operators:						
No hot swapping	27	114	38	728 hours	$ 510	76%
100% hot swapping	0	60	20	383	—	—
80% of setups are hot swapped	—	—	23.6 wtd. avg.	452	$ 317	85%

T4 setup system in Table 4. They add up to about $1.7 million dollars per year. Clearly the big impact is from reducing line downtime.

How do these results compare with others in the same industry? Comparable information is scarce. Jain et al. (1996) followed the dominant approach of optimizing the sequence of jobs to reduce the number of feeder changes needed. Their best implementation gave a 70% to 80% reduction in setup times of the high-speed placement machine but with some increase in run time. Another implementation gave a theoretical reduction of 53% and a documented 31% decrease in single-machine setup times. None of these authors discuss the time for setting up the whole line, the economic value of setup reduction, or implementation costs.

5.4. Other Benefits

After the system was in general use, we observed various other benefits, mostly unanticipated. They were not part of the research design, and although we believe some are important, we have only impressionistic information about them. First were reduced errors from incorrect components, leading to less rework. Despite the extensive error checking under the old system, errors still occurred. The plant did not keep systematic data on magnitude and causes of rework, perhaps due to the political sensitivity of the issue. We believe the incidence of these problems has gone down due to the easier and more reliable setup verification provided by the computerized feeder management system.

There were also miscellaneous assembly-related benefits, many unanticipated. Unscheduled downtime fell, because of fewer problems such as missing or incorrect components, or waiting for the external setup to be completed. 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 used to take as long as an hour, since the replacement reel could be anywhere. The new system has ameliorated many of these disruptions. The feeder setup personnel now locate sufficient reels using the "locate parts" command before the run begins. Even if they still need to find a reel in mid-run, it is much faster.

The computerized management system is also being used in ways beyond its design goals. 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 impact the actual parts preparation operation.

5.5. Development Costs and Issues

These setup improvements were developed over the course of more than a year. We estimate the one-time development costs at about $350,000 as follows: hardware including nine wireless terminals $45,000; lead engineer $100,000; other part-time engineers, programmers, and consultants working $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 $1.7 million per year and costs of $350,000, the payback time is 0.2 years. Using a 20% discount rate, a conservative three year life, and several assumptions about the time sequence of expenditures, these numbers give a net present value of $2.9 million, eight times the original investment. This is roughly the amount saved by not needing to purchase an additional assembly line as volumes increased.

There were a number of implementation issues during the deployment of the system in the factory. All of the operators were kept informed of the system's progress and expected benefits during its development. System training consisted of a number of discrete steps occurring over the life of the project. One-page Quick Start cards created as part of the user training manuals allowed the operators to learn the system tools quickly.

The system was developed on a single line and deployed to the other lines only when it was debugged. This allowed operators to train 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 bugs impeded their progress. The operators were also invaluable in find-

Table 4 Summary of Quantified Economic Benefits

	Old System	New System	% Change	$ Savings/Year With 1,150 setups/Year
Setup downtime, elapsed hours/setup	2.6 hours	0.39 hours	−85%	$1,803,000
External setup time, labor hrs./setup	4.2 hours	3.0 hours	−28%	$54,000
Material handlers	25	20 (equivalent)	−20%	$400,000
Line operators	14	21	+50%	−$560,000
Total benefit per year				$1,697,000

ing system bugs and discrepancies not caught during acceptance testing. Finally, the system had to be deployed so as not to disrupt production. This required coordination with the planners, schedulers, and supervisors.

A common problem with databases used on a shop floor, such as the Feeder Management System, is keeping the data up to date. If users come to distrust the system's accuracy, they have less incentive to use it, which leads to further degradation. In retrospect, our system avoided this for three reasons. First, ease of use was a major design goal. For example, when a material handler moves feeders from one rack to another (a common housekeeping procedure), the *Move Feeder* software tool allows him to update their locations merely by barcode scanning all the feeders and the new rack. More important, the different users responsible for data input (material handlers, feeder setup and machine operators) were also beneficiaries of the system, so that they personally had a stake in accurate data. Third, we observed peer pressure among users to dutifully update the system, thus internalizing the effect of each user's actions on the ability of others to do their jobs well.

6. Conclusion

In Shingo's terminology, "single minute" exchange of dies (SMED) refers to setup times less than 10 minutes. Since he typically worked with stamping presses with multi-hour setups, this was a major accomplishment. Our first contribution was to demonstrate the applicability of Shingo's Single Minute Exchange of Dies approach well beyond the situations it was developed for.

Shingo's fundamental insight of separating internal and external setup activities worked for high-speed placement machines. Another insight in his work is that simple methods are usually sufficient, and where possible we used his "common-sense" techniques. However, our factory had thousands of unique objects used in setups. Our second contribution was to show that modern information technology can be used to extend SMED concepts to such complex situations. We built a computerized information system to assist with feeder management. It uses a modern panoply of computerized tools, such as barcode readers and wireless terminals. Although such techniques were not available to Shingo, they are an extension of SMED principles. For example, a common method in SMED is to visually code feeders to alert operators to potential errors, and indeed, we used color coding to match reels to fixtures. But with more than 3,000 types of reels containing tiny unique parts, and a constantly evolving set of hundreds of different products each requiring a unique combination of parts, we could not use color coding alone. Instead, the barcode readers extend the "color spectrum" by using computers' ability to read digitally encoded information in conjunction with a relational database. This did not achieve the ideal level of foolproofing, which is to make mistakes impossible, but it made them very easy to detect. The effect of these changes was to reduce the incremental machine setup time per feeder from 1.7 minutes to 11 seconds, a nine-fold improvement, and the total setup time from 158 minutes to 24 minutes.

Our third contribution was to show the effects of these technical improvements on economic measures. We estimate that total line setup time was cut by an average of 85%, with savings of $1.7 million per year. From our cost and benefit calculations, we estimate an NPV/cost ratio of 9:1, and a payback period of 0.2 years. 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).

Although we took a comprehensive approach to the bottleneck PCBA process itself, there are other plant-wide setup issues that could further improve setups. One is to standardize components in product design. One reason the plant has so many component types is that engineers specify different vendors for essentially identical parts, such as resistors. Of course standardizing parts would have numerous benefits beyond setups. A second is to look carefully at the way lot sizes and scheduling are determined. After an 85 percent reduction in the cost of setups, it is likely that old methods used to make these decisions should be redone.

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