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A Case Study of the Implementation and Management of Surface Mount Technology at Hewlett Packard's Medical Products Group: Andover Surface Mount Centre[1]

Introduction

Surface mount technology (SMT) is a capital-intensive advanced manufacturing technology that conceptually has been around since the early 1960s, but only relatively recently matured as a viable technology. Today, surface mount is revolutionizing the production of electronic printed wiring boards (PWB) traditionally done by through-hole (TH) technology. In 1990, U.S. manufacturers spent close to $400 million per year on SMT equipment and this figure was expected to double within the next 10 years. SMT typically offers major reductions in board size, improved system performance, and significant direct labour savings over boards made with through-hole technology.

This case study describes the implementation of SMT at Hewlett Packard's (HP) Andover Surface Mount Centre (ASMC). ASMC makes digital and analogue boards for HP's Medical Products Group (MPG) as well as other HP companies. By all measures, the SMT implementation at ASMC was a major success. Today ASMC is widely acknowledged as one of the best surface mount manufacturing facilities inside HP.

The implementation timeframe for this case stretches from the early 1980s up to the present. Many of the important issues in this case unfolded from 1985 to 1990. Information in this case was collected during a series of interviews with design engineering, printed circuit (PC) layout, manufacturing engineering, and manufacturing personnel. Other secondary reports and memos were also reviewed and incorporated into this case study, along with direct observations made during numerous site visits and two detailed factory tours.

Background

Ultrasound imaging uses high-frequency sound waves to create accurate images of the human body's interior. Sound waves transmitted through the body reflect off of tissues and return an echo to the transducer. The echo contains information about the tissue characteristics, and can be electronically converted by a computer into two-dimensional images for medical analysis. Because high-frequency sound waves cannot penetrate bone or air, ultrasound machines are especially useful for imaging soft tissues to view organs for cardiology and vascular diagnosis. A major advantage of ultrasound machines, over rival techniques such as X-rays or exploratory surgery, is that they are noninvasive (no cuts or injections are required) and there is no exposure to harmful radiation or chemicals. Furthermore, ultrasound's typical system cost of $50,000 to $200,000 compares very favourably to the over $1 million price tag of a computerized axial tomography scanning (Cat-scan) or magnetic resonance imaging (MRI) machine. This modest purchase price in comparison

[1]This case was developed for use in classroom discussion and is not intended to necessarily illustrate appropriate or inappropriate management practices. Case author: Mark Frohlich, Boston University, 1996. Acknowledgement is made to Jeffery Miller and Steve Rosenthal, Manufacturing Roundtable of Boston University. The funding for this case production was provided by the Australian federal government's Department of Industry, Science and Resources.

to Cat-scans and MRIs, in combination with lower training, maintenance, and downtime costs, as well as real-time images, spurred an explosion in ultrasound system sales in the 1980s. As seen in Table 1, dollar shipments in the ultrasound market increased sixfold while the number of units delivered more than tripled from 1980 to 1991.

Until the early 1980s, ultrasound equipment used mechanical transducers to produce two-dimensional black-and-white images. In 1981, Hewlett Packard's Medical Products Group, located in Andover, Massachusetts, revolutionized the industry with a phased array system that offered greatly improved image quality. In 1984, Irex (a subsidiary of Johnson & Johnson) introduced another breakthrough with colour ultrasound equipment. In 1986, MPG once again upped the ante when it successfully combined Doppler technology with colour imaging. This allowed doctors for the first time to monitor both the direction and velocity of blood flow in organs such as the heart. As seen in Table 2, by the mid-1980s MPG had become a market leader for ultrasound systems.

TABLE 1 Ultrasound Industry Dollar and Unit Value Shipments: 1980–1991 ($ value in millions)

Year	*Value*	*Units*	*Year*	*Value*	*Units*
1980	$150	2,725	1986	$432	6,950
1981	219	3,785	1987	540	7,475
1982	243	4,660	1988	663	8,380
1983	269	5,350	1989	801	8,975
1984	306	5,760	1990	836	9,510
1985	350	6,550	1991	908	9,950

Source: HBS Case HP Imaging Systems Division.

TABLE 2 U.S. Market Share Positions of Leading Ultrasound Manufacturers: 1983–1991

Company	*1991*	*1990*	*1989*	*1988*	*1987*	*1986*	*1985*	*1984*	*1983*
Acuson	1	1	2	2	2	3	6	6	-
Aloka	6	7	7	6	8	11	-	-	-
ATL	3	3	3	3	3	2	2	1	1
Diasonics	5	5	5	4	4	4	4	2	2
GE	7	6	6	5	5	5	5	5	7
HP-MPG	**2**	**2**	**1**	**1**	**1**	**1**	**1**	**4**	**4**
Hitachi	10	11	11	12	-	-	-	-	-
Interspec	9	9	8	8	7	7	13	-	-
Siemens	8	8	17	15	-	-	-	-	-
Toshiba	4	4	4	7	6	6	10	10	10

Source: HBS Case HP Imaging Systems Division.

Factors Setting the Context of Change

External Influences

Competition. The most important performance feature all ultrasound manufacturers competed on was image quality. A key driver of image quality was the number of channels in the transducer. Throughout the 1980s transducer channels rapidly grew from 48 or 64 to 96 or 128. By the early 1990s a number of companies were working on 192 or 256 channel systems and even three-dimensional imaging.

Given the "cost-plus" structure of much of the U.S. health care industry, price was for many customers a secondary consideration. In certain markets, however, health care cost containment was becoming more important. In 1983, the U.S. government mandated that all Medicare expenses be part of a prospective payment system (PPS). With PPS, hospitals were reimbursed for tests based on regional costs, not on an individual hospital's costs. In 1991, PPS was extended to capital expenditures. Similarly, by the early 1990s, private health insurance companies began to balk at rising medical costs and HMOs had emerged as a dominant cost control model. Finally, with the rising national concern over health care costs in 1993–1994, capital-intensive diagnostic equipment's price had become an important consideration.

MPG faced aggressive domestic and international competition in the 1980s. As suggested by Table 2, Acuson, a California company founded by a former HP engineer, quickly followed MPG's lead and introduced Doppler colour flow in 1988. Other U.S. companies such as ATL (Advanced Technology Laboratories), Interspec, Biosound, GE, and Siemens likewise offered competitive products in terms of price and performance. Toshiba, the world's leading seller of ultrasound systems, was reported to have the largest R & D budget of any ultrasound company. Other international electronic giants like Hitachi and Philips were likewise attempting to expand their U.S. market shares. Foreign competitors, in particular, were threatening to dominate the low-end/low-cost segment of the ultrasound industry.

Marketplace. The U.S. ultrasound business consisted of three distinct markets as shown in Table 3. Originally, ultrasound systems were purchased almost exclusively by either large hospitals or imaging clinics. A typical machine in this category could cost anywhere from $150,000 to $250,000. These customers typically bought high-performance systems with the densest available transducer channel capabilities for superior image quality. Large hospitals and imaging clinics also tended to buy "full feature" systems such as Doppler and flow-flow. From the manufacturer's perspective, printed wiring board size or "real estate" was an important consideration with high-performance systems. As more transducer channels and features were added to high-end systems in the mid-1980s, the physical size of systems and board density were starting to reach their limits of manufacturability.

Smaller urban and rural hospitals composed the second customer group. These products had somewhat less imaging performance than high-end systems due to fewer transducer channels and also offered fewer optional "bells and whistles." A typical machine in this segment sold for $100,000 to $150,000. Since electronic components were also relatively densely packaged inside midrange systems, existing technologies and manufacturing methods likewise had trouble accommodating these product lines.

The final market segment was for very small hospitals and private physicians. As cheaper systems became available in the 1980s, independent practitioners and outpatient clinics started buying low-end ultrasound systems. A typical machine in this niche sold for under $100,000. In this market, the price-performance ratio of systems was important. In other words, the closer the performance of a system was to mid- and high-performance systems and the lower the price, the more likely customers were to buy them. Given the limited physical space and technical expertise

TABLE 3 Market Segments and Competing Ultrasound Products

Market	*Customer*	*Competitor*	*Products*	*Prices*	*Features*
High Performance	Large urban or teaching hospitals	**HP-MPG**	**Prism 1500** **Prism 1000 Enhanced**	>$150K	Phased array 96–128 channels
	Imaging clinics	Acuson	128 XP		Superior image quality
		Toshiba	SSH-140AC		Colour flow, Doppler
Mid Performance	Midsized urban hospitals	**HP-MPG**	**Prism 1000 Basic**	$90–$150K	Annular or phased array
	Rural hospitals	ATL	Ultramark 9		48–64 channels
		Toshiba	140A		Moderate images
					Colour flow, Doppler
Low Performance	Small hospitals	**HP-MPG**	**Sunrise**	$50–$90K	Mechanised, annular, or phased array
	Private practices	Interspec	Apogee		48–64 channels
		Vingmed	CFM750		Acceptable images quality
		Biosound	Genesis		Colour flow, black & white

Source: HBS Case HP Imaging Systems Division.

available to most private physicians and outpatient clinics, the overall size of an ultrasound system, its reliability, and its ease of use were also important considerations.

Internal Influences

Technology. Ultrasound machines, as with almost all other electronic scientific and medical equipment, originally relied on through-hole technology. TH had emerged in the 1960s and 1970s as a relatively cheap, flexible, and robust way to produce PWBs. By the early 1980s, TH was a very mature technology. Insertion machines for placing components on boards and wave-soldering allowed for relatively low-cost production. Unfortunately for ultrasound manufacturers, an increased number of transducer channels and features were starting to push TH process capabilities to the limits of its capabilities. In some cases the total number of boards required meant that more and more components were being crowded into limited cabinet space. In other situations, features were limited to a single-sided board and relatively costly accommodations had to be made in order to connect options across two or more boards. Board complexity not only added to engineering design costs, but also increased manufacturing labour costs. TH parts were becoming so tightly packed that they exceeded automation capabilities. Finally, since the second most expensive item in PWBs is the board itself, manufacturing material costs were beginning to climb as standard and optional features required more and more board space.

In the early 1980s, many of HP's electronics divisions were facing problems similar to MPG. Customers were demanding greater performance, computers were getting smaller and faster, and finished board costs needed to be reduced. In 1983–1984, HP's CEO, John Young, asked that his 45 manufacturing divisions each take 10 percent out of their board costs for a combined cost savings of $100 million. At the same time HP's top management formed the Manufacturing Engineering Council (MEC) to help make board cost reduction recommendations. Although originally chartered to evaluate existing manufacturing practices, the MEC also took a close look at emerging electronic packaging alternatives. Impressed with the technology in Japanese products such as the Sony Walkman, the MEC recommended that HP begin investing in surface mount technology. Purchasing a new process technology was not the near-term cost solution HP's management was looking for, and the MEC was disbanded. The stage was set, nevertheless, for future adoption of SMT at HP.

Many divisions began to realize that 100 percent TH technology was starting to constrain new products and they were interested in pursuing SMT. Some divisions (like calculators in Corvallis, Oregon) had already switched from TH to SMT in the early 1980s. The corporatewide movement to SMT, however, posed a major cultural dilemma at HP. Traditionally, HP's 45 divisions were highly autonomous. Each division was charted to go after a market segment and always had both its own engineering and manufacturing capabilities. The relatively high costs of SMT equipment made it prohibitively expensive for each of HP's 45 divisions to develop surface mount manufacturing capabilities. Taking manufacturing away from previously self-sufficient divisions ignited a major cultural debate. Some top managers even went so far as to suggest that only a single surface mount manufacturing centre was necessary to supply all of HP's businesses. Hal Edmonson, HP's senior vice president of manufacturing, helped drive the push for SMT while limiting the number of divisions that would develop SMT capabilities. The corporate technology strategy that emerged was that, of the 45 divisions using TH, only a fraction would migrate to SMT manufacturing. Those divisions in which SMT board production was centralized would in turn manufacture PWBs for all of HP's other businesses. To help enforce this policy, Hal Edmonson required that his signature be placed on all major SMT equipment purchases. The stage was set for competition among these 45 divisions to be one of the ones (ultimately 15) that eventually ended up with SMT manufacturing capabilities.

Recognition of Need to Change

External Drivers

Foreign Competition. By the mid-1980s, Japanese competitors were directly threatening the low end of the ultrasound market. Specifically, there was a niche for machines that cost a quarter to one-third of high-end systems (roughly $40,000 to $50,000) yet offered decent image quality along with flow-flow capability. While lower performance machines only represented 10 to 15 percent of MPG's sales, there was concern that, as with the consumer electronics and automobile industries, once the Japanese controlled the low-cost segment they would next attack HP's more profitable mid- and high-end ultrasound business. The Japanese, in fact, had already made major investments in TH production processes and had a cost advantage over most U.S. competitors. All other foreign and domestic ultrasound manufacturers likewise relied on traditional TH technology. In the mid-1980s none were converting to SMT, although some of MPG's competitors, like ATL, were rumoured to be considering it.

Internal Drivers

Design and Operational Inefficiencies. In the mid-1980s, MPG's design engineering and manufacturing functions were under growing pressure to accommodate greater ultrasound system capabilities, reduce production costs, and improve quality. In design engineering, even though customers demanded more and more features, the size and weight of ultrasound system carts could not realistically be increased any more. Some of the original through-hole phased array system boards were already very complex: several PWBs had hundreds of TH components and some systems had up to 5,000 electrical components.

Similarly, MPG's manufacturing was under growing pressures. Even though customers were somewhat price insensitive, in the mid-1980s new features quickly drove an average system's cost from approximately $120,000 per unit to well over $200,000. MPG's Andover manufacturing function was expected to help hold down production costs wherever possible so the price of high-performance machines did not spiral hopelessly out of control. MPG's board productivity and quality likewise had room for improvement. Analogue board yield was 80 percent and cycle-time[2] was a relatively long six weeks. System reliability in the field was about average for the industry.

Technology Strategy. In the mid-1980s MPG was the market leader in ultrasound systems, especially in high-performance systems suitable for cardiac diagnosis. MPG's technology strategy was to continually evolve the high-performance ultrasound system as soon as each new technological innovation became practical. The strategy included adding colour flow processing, installing a larger imaging aperture, and expanding disk storage space. As health care came under further pressure to reduce the costs of delivering medical services, MPG's management grew concerned that the company might be too vulnerable to lower-cost, acceptable performance competition.

In 1985 MPG formed a separate project team at its Andover plant to develop a complementary ultrasound system with similar diagnostic capabilities as the high-end system at a third of the cost. Early on it was decided that the new system would have a mechanical sector scanning "front-end," rather than phased array, and would not include colour flow processing circuitry. In all other specifications, however, the new system was to meet or exceed the high-end ultrasound system.

Process of Transition

Initiation. MPG's SMT journey took much of the 1980s, and a timeline is shown in Exhibit 1. By the early 1980s, various pieces of Andover's TH equipment were either worn out or obsolete. In 1982, Bert Anderson, manufacturing technology manager for MPG, initiated a study of TH technology to see what changes could be made to the existing PWB production processes in order to improve efficiency and quality. Andover's manufacturing engineering department was chartered, in effect, to do whatever was necessary to overhaul TH. During the course of this analysis it quickly became apparent that, rather than reinvesting in TH, a better strategy might be to move to SMT. Steve Kalenik, a manufacturing engineer hired by Bert to improve TH, visited other companies using SMT and contacted vendors to get component samples. Several trial boards were made after-hours in manufacturing, and hands-on demonstrations were held for design engineers using a makeshift vapour phase SMT process. Based upon what they saw in industry and read in technical journals, Bert and Steve quickly became active champions of SMT. For several years manufacturing, under the leadership of Bert and Steve, formed an SMT "skunk works" and continued to develop and advocate surface mount technology inside MPG until a product line committed to the new technology.

Before SMT was introduced at Andover, engineering always took the lead in product and process changes. Since the SMT implementation, manufacturing has led engineering in process changes.

[2]ASMC calls what is typically known as throughput time cycle-time, the elapsed time from when an operator first touches the raw board until it passes final tests.

EXHIBIT 1

Surface Mount Technology Timeline

	1981	*1982*	*1983*	*1984*	*1985*	*1986*	*1987*	*1988*	*1989*	*1990*	*1991*	*1992*	*1993*	*1994*	*1995*
First Prism system shipped	*														
Andover manufacturing TH study		*	*												
TH production system improved				*	*										
Andover SMT prototype experiments		*	*	*											
HP corporate implementation teams			*	*											
Sunrise system designed					*	*									
Dynapert system purchased							*								
TH manufacturing phased out							*								
First Fuji system purchased								*							
Second Fuji system purchased									*						
Third Fuji system purchased											*				
First Sunrise systems shipped							*								
Prism system redesigned from TH to SMT							*	*							
First revised Prism systems shipped									*						
Infrared ovens switched to convection														*	

Because the very profitable high-performance product line was originally developed using TH technology, and it was HP's only existing ultrasound system, from 1982 to 1986 there was no new product development project or budget under which Andover's manufacturing could introduce SMT. During the next two years manufacturing informally acted as SMT liaisons with engineering and other departments and educated them on the benefits of SMT. During this time period manufacturing also spent a lot of time refining its existing TH board production capabilities and vendor base in anticipation of someday migrating to SMT. Notably, vendors' raw board interlayer shorts and part delivery problems were solved.

Adoption. In the mid-1980s the inherent risks of moving the market-leading high-performance system to the relatively unproven SMT process was unacceptable to many managers at MPG. By 1985 growing performance, cost, and quality issues had begun to mildly squeeze the Prism system line, but senior management still declined to convert this profitable product line from TH to SMT. Consequently, Andover's manufacturing managers could do little but continue educating other departments on the potential benefits of SMT, and attempt to recruit engineering project managers responsible for new product development to include surface mount in their plans.

Fortunately for Andover's SMT champions, at about the same time in the mid-1980s, MPG decided to go ahead with a low-cost system later to be named Sunrise. Sunrise was originally partially designed using TH technology, but it quickly became apparent that a low-cost, high-performing "desk-top" system was impossible to produce using TH. Even under the most optimistic assumptions, including a fully automated TH assembly process, the new system still cost $500 over the target number and could not fit in one small desktop package. SMT emerged as the only viable way to achieve the ambitious goals laid out for Sunrise. At first, the Sunrise project manager, Al Langguth, was skeptical about actually using SMT. Faced with no other realistic alternatives, Al checked with engineers at another HP division and heard very good things about SMT. By 1986, Al had become an enthusiastic cochampion along with manufacturing for SMT. Shortly thereafter the surface mount equipment authorization was approved under the budget "umbrella" of the Sunrise project.

The Sunrise product was designed to use almost all SMT components. Engineering and manufacturing contacted component vendors and collected all the existing SMT components they could. In some cases the types of SMT components Sunrise needed either did not exist or were still in the prototype stages at chip manufacturers. Since all its combined businesses made HP a major purchaser of electronic components, the Sunrise project team was able to put strong pressure on manufacturers such as Motorola and Texas Instruments to quickly develop new SMT parts. Several times vendors even developed SMT components on a special hand-made basis for Sunrise. In one case, with the central processing unit (CPU) board, the wait for SMT components was unacceptably long. The Sunrise team went ahead and designed that board using TH technology so that working systems could begin environmental and clinical testing. Later, when SMT CPU components became available, the board was redesigned using surface mount parts.

As SMT components became available, trial boards were hand-assembled by Andover's manufacturing department and driven to the reflow ovens at local equipment vendors and laboratories for soldering. These experiments gave manufacturing's technical people the confidence to convince the nontechnical people that SMT really worked. Manufacturing even developed a portable "SMT kit" (complete with solder paste stencil, squeegee, raw boards, and SMT components) that was taken from equipment vendor to equipment vendor to evaluate SMT process techniques and build trial boards. In the case of some critical new SMT components, Andover only had one or two part samples available on hand that vendors had prereleased to them. In these situations manufacturing was under great pressure to make the process work with the first trial run so the project would not be delayed by ruined components or incorrectly assembled boards.

Once enough trial boards were produced, reliability tests were begun to pass MPG's rigorous quality assurance standards and demonstrate Good Manufacturing Practices to win Food and Drug Administration (FDA) approval of the new technology. Indeed, the ASMC eventually became so good at SMT manufacturing that it later trained over 50 FDA inspectors on how to assess the new board-making process.

Midway through the Sunrise development process a parallel low-cost ultrasound system project in Germany was folded into the Andover project. Although not directly related to SMT, as part of Sunrise, Taguchi methods were widely used to develop robust designs and manufacturing processes. A PhD statistician was even hired to help evaluate Taguchi experiments. In addition to Taguchi experiments, each Sunrise board was subjected to tough analyses involving power consumption and clock speed. In total, unexpected engineering and manufacturing delays, the merger of the Andover and German systems, and problems obtaining SMT components caused the Sunrise project to miss its target launch date by approximately one year.

It is important to note that no formal investment justifications were done for SMT. The decision to adopt SMT was made mainly based upon strategic considerations. In fact, traditional cost-benefit analyses were done and indicated that SMT should not be invested in. Other economic analyses were done using spreadsheets developed by engineering that projected how product material and labour costs would drop if SMT versus TH components were used. Numerous SMT layouts were also simulated and evaluated by Andover's manufacturing engineering until a good shop-floor design was achieved.

The adoption of SMT by the high-performance ultrasound product line was a more difficult process. The procedure lasted from 1987 to 1988, and the original TH high-performance system was completely redesigned using SMT components. The new high-performance system based on SMT was called Prism. MPG's Prism system was, at the time, one of the most sophisticated products any U.S. company had ever developed using SMT. The Prism product line had many complicated boards, and was an order of magnitude more complex than even relatively sophisticated ultrasound systems such as the new Sunrise product. Prism's boards not only had tremendous board density but many were also double-sided. In some cases, Prism's new SMT boards had 1,500 discrete components. In addition to the available features and options of the Prism product line, there were also a greater total number of boards to produce. Using SMT, the number of total components in a Prism system eventually mushroomed to over 27,000. Even after the initial SMT conversion process, it took the design engineering and manufacturing departments nearly another year to work out all of the bugs in the new Prism ultrasound system.

Content and Substance of Change

The Production System. HP corporate encountered design and equipment standardization problems with SMT. SMT "implementation teams" called the Technology Management Team (TMT) and the Process Management Team (PMT) were therefore set up by corporate to help determine companywide design and equipment standards. From 1983 to 1987, HP's implementation teams developed numerous SMT product and process standards. HP held an SMT "bake-off" among rival oven technologies to determine which vendor to standardize on. Vitronics' oven ultimately won. Similarly, all major SMT placement machines were evaluated before HP decided to standardize on Fuji's equipment. The implementation teams also developed standards for SMT board sizes and pad shapes. Wherever possible, Andover used these corporate standards to guide its own SMT implementation.

SMT equipment was bought at Andover in three distinct phases starting in 1986. In the first phase a Vitronics reflow oven was bought for approximately $25,000. This oven allowed ASMC to more easily produce test boards and further familiarize engineers and operators with SMT manufacturing processes. In the second phase, starting in 1987, a Dynapert MPS 515 picks and place machine was ordered for $400,000. At the same time a corporate Technology Management Team was chartered to determine which SMT equipment was the best and what vendor would become HP's standard. Amid political controversy, Andover's Dynapert order was put on hold until the TMT evaluation was finished. As it turned out, Dynapert won the TMT competition so Andover's originally ordered Dynapert MPS 515 was taken off hold and finally delivered. A second Dynapert machine was leased shortly after the first one. A year later, the TMT was replaced by the Process Management Team. The PMT held a second competition and HP corporate this time standardized on Fuji equipment.

From the beginning stencils were purchased from an out-of-state supplier, and stencilling of solder-paste was done manually. At this point a process engineer was also hired to help perfect the new technology. In the third phase, starting in 1988, a $500,000 Fuji machine was purchased and a second assembly line was set up. Shortly thereafter, another Fuji machine was purchased and a third production line was installed in order to handle growing Prism business and subcontracted board volume from other HP companies. Today Andover's manufacturing department is formally known as the Surface Mount Centre.

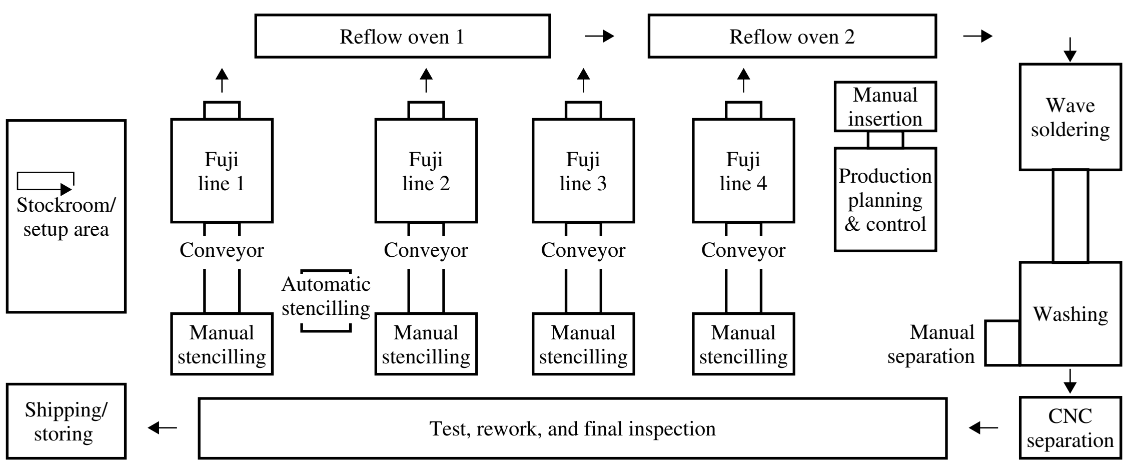
Adaptation

Technological Change. In the transition from TH to SMT, the shop floor underwent substantial change. All the existing TH machines were removed except for the wave soldering line. Any existing TH boards were immediately subcontracted out. The shop floor was reconfigured into a smaller area with a classic U-shaped flow from the stockroom and staging area through the Fuji machines, reflow ovens, manual TH insertion, wave solder, board washing, board separation, final test, and shipping departments (see Figure 1). One of the most fundamental changes involved reversing the shop floor from a batch operation with massive work-in-process (WIP) under TH to a continuous flow with as little WIP as possible using SMT.

No internal changes were made to any of the Fuji machines or reflow ovens, and very few other modifications were made. Operations were purposefully kept as simple as possible. Even the various assembly lines were not connected by any conveyor systems. One significant adapta-

FIGURE 1

Surface Mount Centre layout



tion, however, was to develop a fixture for prestaging component part reels on a pallet so that it could be quickly exchanged with another pallet during the setup of a Fuji machine.

A major administrative adaptation was made in MPG's "above-the-shop-floor" information systems. A sophisticated Product Information Management (PIM) system was developed so that board designs from inside MPG's engineering groups, as well as any other company on HP's worldwide network, could be downloaded to ASMC. To summarize the PIM, engineering and PC layout [department] design boards using a popular computer aided design (CAD) package. This data is transferred using translators to manufacturing's information system. Manufacturing, in turn, translates these files into a board "recipe." A MRPII system is also used by manufacturing to help control and procure inventory. The PIM system allows the ASMC to complete prototype boards in less than 24 hours and also helps minimize the number of component misloads (incorrect insertions of components onto boards) in regular production boards. It is important to note that the PIM system does not yet interface directly to the Fuji machines in a true computer-integrated-manufacturing (CIM) system. This is in keeping with ASMC's philosophy of "focusing on results, not on tools" and represents a conscious decision to avoid building a costly "information factory."

A final technical adaptation was in the area of quality control. With TH, MPG relied upon 100 percent in-process and final inspection. With SMT and flow manufacturing, in-process inspection was gradually phased out in favour of statistical process control (SPC). Today, Andover's manufacturing managers are firm believers in SPC. SPC has proven particularly beneficial in assuring quality through the soldering process.

Organizational Change. The transition from TH to SMT affected departments differently. Logical circuit schematic design engineering had almost no trouble converting from TH to SMT. Circuit schematic design on their CAD system was essentially the same for TH and SMT. Design engineers, however, were greatly affected by new demands SMT placed on prototyping boards. With TH, design engineers actually had "laboratory" component stock and would manually build many of their own trial boards. With SMT this was no longer possible due to the much smaller size of discrete components along with the need to solder paste and reflow boards. Design engineers now had to rely on manufacturing to make trial boards. Similarly with TH, design engineers could relatively easily test prototype boards. Because a similar-sized SMT board is typically so much more densely covered with components than a TH board, connecting test equipment to surface mount parts now often became a real challenge for design engineers.

The PC layout department, responsible for translating logical circuit schematic designs into board physical design "blueprints," also struggled during the SMT implementation process. The density of SMT packaging and the greater use of multilayer boards made it difficult for some PC layout designers to make the transition from TH to SMT. SMT dramatically changed board complexity because many more components could now be placed on a PWB. In some cases up to four times more components are placed on SMT boards as compared to a similar-sized TH board. Since SMT components are placed on top of four or six multilayer boards, the number of "vias" (holes connecting different board levels) likewise increased by 30 percent over an identical-sized TH board. SMT component density, in combination with many more vias that had to be carefully positioned, greatly increased PC layout time. With TH the typical layout time was two to four weeks for a new board. When MPG first cut over to surface mount designs layout time skyrocketed to two months. Only recently has SMT board layout time been reduced back to the two to four weeks of the original TH process. On a per-component basis, this represents a major net improvement over through-hole times. In addition to more complicated designs, PC layout also had to develop, from scratch, libraries of standardized symbols and component specifications. PC layout also helped optimize design of pads using Taguchi methods.

Andover's shop-floor workers were likewise called upon to make radical changes in work procedures during the transition from TH to SMT. Andover's manufacturing management made a strategic decision to develop a core competency in SMT. Part of this strategic decision was to immediately eliminate all TH manufacturing at Andover. All TH board-making equipment was replaced by new SMT processes and any remaining TH work was subcontracted out. Employees previously trained to do only one highly skilled manual job such as soldering had to learn how to do multiple tasks on a Fuji line.

This represented a major shop-floor cultural change. With TH, manufacturing workers were assigned to a workstation and batches of materials came to them in boxes. With SMT, assigned workstations were removed and people now moved to where the work was in the process.

Similarly, Andover's manufacturing management dramatically changed with the arrival of SMT. With TH production there were three shop-floor managers covering the major operations of "auto insertion," "hand load," and "test." These managers were strongly oriented toward batch production and none made the transition to SMT flow production. New supervisors, willing to give flow manufacturing a try, were quickly promoted from within to lead Andover's SMC.

Three other areas were changed as part of the transition from TH to SMT. First, performance measures were radically modified. Under TH, in the auto insertion, hand load, and test departments, performance measures were respectively based on the number of component placements per shift, number of hand-loads per shift, and number of boards tested per shift. In effect, each of these departments collectively suboptimized their processes to the detriment of the entire manufacturing function. With SMT, performance measurements were changed to one standard for everybody in ASMC: number of placements shipped. This single performance measure reflected Andover manufacturing management's philosophy of "holding the goal at the highest level." This also helped ensure that the shop would not relapse into its old batch manufacturing habits.

A second change involved shop-floor control and scheduling. Andover's SMC concentrated on reducing cycle-times and keeping WIP moving. A special position—called the "line engineer"—was created to schedule and flow shop-floor production. The line engineer's job was to teach the shop floor how to behave and function as a flow, not a batch, operation. The line engineer constantly moved back and forward through the process and spotted WIP building up. Whenever excess WIP was identified, the line engineer had the authority to immediately reallocate resources to keep things flowing and was empowered to change equipment layouts. The line engineer position was, from the beginning, a temporary assignment. Eventually shop-floor workers began thinking like the line engineer and the ASMC started functioning like a flow shop. When the line engineer position was no longer needed it was eliminated.

The line engineer also helped reduce cycle-times. SMT's greater volume really showed the importance of short cycle-times. The relatively slow pace of TH production, even though it was a batch operation, never piled up nearly as much WIP as SMT was capable of. With SMT's volumes, existing problems were made much worse by long cycle-times. Wherever possible, the line engineer attempted to reduce cycle-times. Principles from the *The Goal* were also used to help motivate employees, identify constraints, and remove bottlenecks.

Finally, with the growing importance of cost in the health care industry, Andover recently implemented an activity-based cost accounting system to help evaluate and control total product costs. Four key cost drivers were identified by manufacturing: (1) number of auto-loaded parts; (2) number of hand-loaded parts; (3) number of discrete tests; and (4) number of components purchased. This information is widely shared with engineering to help minimize the costs of new board designs for existing systems.

Acceptance

Manufacturing. SMT was a strategic decision that MPG's senior manufacturing management was firmly behind. Manufacturing senior management quickly accepted SMT based upon the significant relative advantages the new technology offered over TH. Manufacturing's workers and supervisors, consequently, had no choice but to accept SMT. As mentioned above, TH manufacturing line managers never accepted SMT and new managers for the ASMC had to be promoted from within. Similarly, some shop-floor workers quickly accepted SMT and some resisted. In general, the more job tenure and the better educated/trained employees were in the existing TH processes, the more eager they were to accept SMT. Typically, the best TH workers were the ones that most successfully transitioned to SMT production. In some cases, workers never made the transition and either retired or transferred to other operations.

Engineering. After some initial hesitancy Sunrise design engineering quickly accepted SMT based upon its board size and production cost advantages. Indeed, everyone on the project team eagerly anticipated the transition to SMT and the associated growth in their own skill sets. Prism design engineering, on the other hand, was very reluctant to make the changeover from TH to SMT, despite the obvious advantages of SMT. As one person put it, the Prism group had developed a "John Wayne attitude" that they could do whatever they wanted to. As another person described the Prism team, "They didn't care about the process technology, they only concentrated on the technical aspects of design." In fact, it was not until manufacturing ceased TH board production in-house and began subcontracting it out at higher costs that senior management finally convinced the high-performance ultrasound system engineers to design a new product line using SMT.

Finally, some designers in PC layout quickly accepted SMT and some did not. For some PC layout employees, the added board layout task complexity triggered by SMT component density and the routing of vias proved to be an important hurdle to accepting surface mount. Recent college graduation and formal training in complicated multilayer board design along with low job tenure seemed most related to the decision to accept the new technology. Indeed, at least one long-time employee in this department never made the transition from TH to SMT layout.

Politics of Change

Intradepartmental Politics. During the transition from TH to SMT, there was relatively little "office politics" inside most departments. As mentioned above, the existing manufacturing supervisors were planned out of the new SMT process. Similarly, highly skilled TH workers like the manual solderers resisted the change and shop-floor morale plummeted. To help improve morale, whenever possible TH employees were retrained to perform SMT tasks. At one point temporary workers were even brought in from the outside to help meet the exploding demand for new SMT process work. These temporary workers, by smoothing over peaks and valleys in demand, helped ensure that the ASMC was a success in its critical first few years of operation.

The second "political" problem in manufacturing involved changing people's mind-set from batch to flow production. During the first year of Sunrise, SMT production shop-floor workers continued to produce boards in large batches. Problems became even worse when Prism board production began. At one point the massive Prism volumes choked the shop floor with WIP and nearly brought all production to a halt. It wasn't until the introduction of one standard performance measure for all of manufacturing, "number of parts shipped," and the formalization of the line engineering scheduling job that shop-floor workers were trained and learned to change their perspective from batch to flow.

Interdepartmental Politics. The major interdepartmental political conflict involved Prism design engineering, PC layout, and manufacturing. As suggested above, the culture of the Prism group was entrepreneurial and the tendency was to do things loosely and "make changes on the fly." Manufacturing's culture, on the other hand, was to tightly control every detail. The PC layout group, in the middle of the process flow between design and production, moderated between these two extremes. Confounding the problem was relatively poor communication among all three groups. Most of the political conflict between the groups was during the prototyping stages. During prototyping, product uncertainty was high and a lot of poorly communicated changes were made by either engineering to designs or manufacturing to processes. A particular focal point of controversy was in the shape and location of pads for placing SMT components.

The political conflicts between Prism design engineering and manufacturing stands in stark contrast to the Sunrise project. Throughout Sunrise, design engineering and manufacturing had excellent communication. Sunrise project management even went so far as to change the compensation structure of its engineers to ensure that they designed boards that could be manufactured using ASMC's Fuji equipment. Key engineering design goals for the Sunrise project team are summarized in Table 4.

A key part of this process was Total Quality Control (TQC) teams. TQC meetings were especially valuable for cleaning up problems with boards. These teams met weekly, strictly to deal with any design or process problems. In these TQC meetings every board failure was evaluated using techniques like Pareto analysis. In addition to TQC meetings, manufacturing engineers were invited to sit in on Sunrise engineering design meetings and design reviews. In 1989, Quality Function Deployment was brought in to facilitate even greater communication between engineering and manufacturing.

Interplant Politics. In the mid-1980s, there was often fierce competition among plants to become SMT manufacturing centres. Inside MPG the Waltham and Andover plants vied to become the group's sole SMT centre. Waltham manufactured bedside monitors, and some of its employees had originally helped staff the Andover location in the late 1970s. In 1985 Waltham believed that it should become the SMT centre. Andover, meanwhile, had the very profitable high-performance ultrasound product line and was the location for the new Sunrise development project so it thought it should become the SMT centre. In the end, Waltham did a lot of numerical analyses to try and demonstrate that it should be the group's SMT site, while Andover conducted a lot of experiments and built numerous trial boards. Based upon Andover's greater hands-on experience, MPG's senior management decided in December 1986 that the SMT centre should be located in Andover.

As an aside, so bitter was the rivalry between the two MPG divisions for the SMC that after the decision Waltham swore it would never buy boards from Andover. Waltham initially carried through on this threat and sourced all of its boards from an HP plant in Germany instead of Andover (which is just 30 miles away). Andover was counting on Waltham's board volume when it had originally planned for the scheduling and overhead absorption of the ASMC. This loss in volume forced ASMC to cut cost to the bone in order to survive. In effect, this rivalry with Waltham drove Andover to improve its operations much more than it might normally have. Ironically, SMT and Andover's accompanying manufacturing improvements so reduced production costs that when Waltham's German board supplier could not reliably deliver boards, Waltham

TABLE 4 Sunrise Project Team: Engineering Design Goals

Engineering Design Goals

- No more than 200 unique part numbers.
- No more than 2,500 total electronic parts on all boards.
- No more than 100 part numbers on any boards.
- No manually loaded parts on any boards.
- No temperature rise greater than 10 degrees Celsius on any board.

was eventually "compelled" to buy tens of thousands of boards from Andover. In the long run, ASMC was ultimately in even a stronger competitive position with their hard-won manufacturing improvements along with Waltham's added board volume.

Operation of New Practices

Optimization. Ramp-up of SMT occurred very rapidly. In five to six months the ASMC went from placing 200,000 components for Sunrise to over 8.5 million parts per month. Before, with TH, 100 employees per shift worked two shifts to place 200,000 parts per month. With SMT, 150 total employees across three balanced shifts placed 8.5 million components. It is worth noting that ASMC's operations always run three shifts per day, five days per week, in order to avoid "cold start-ups" at the beginning of every first shift.

Early in the SMT implementation process, ASMC standardized on board sizes and the number of boards per panels. Today, 250 different kinds of boards with about 12 million components per month are run through the ASMC. Boards are made for MPG's product lines as well as other HP divisions. Typical board lot sizes range from 20–2,000 boards. Capacity utilization at the ASMC is planned for 80 percent. This allows 10 percent capacity for surge demand, and also sets aside 10 percent of available capacity for prototyping new boards.

Infusion. ASMC currently has four dedicated Fuji SMT lines. Capital costs for the entire SMT project were over $4 million. Approximately 93 percent of the components on a board are SMT and the remainder are TH. TH is mainly used for components that generate heat or take a lot of strain (like board connectors). The Fuji machines are used to place all SMT components and are run on average 24 hours per day, five days per week. Whenever necessary, overtime is worked on Saturday. Most TH components are inserted manually and automatically wave soldered. Some special TH components are manually inserted and hand-soldered by skilled labourers. On a relative scale, manufacturing's cost accounting system charges customers "X" for each SMT component automatically inserted and reflow soldered. TH items with wave solder are charged "10X" per component. Any manually inserted and hand-soldered components are billed at "100X" each. This sharp escalation in the cost for non-SMT board components acts as a strong incentive for engineering to keep the percentage of surface mount components in their new designs as high as possible. Today, because of long component lead times and chip shortages, a relatively large amount of raw inventory is kept on hand. As in many organizations, marketing's forecasts are often imperfect so manufacturing must also carry additional inventory to cover unforeseen demand. Inventory turns are therefore roughly five to six times per year.

In 1994, MPG switched from four infrared ovens to two state-of-the-art ATMOS convection reflow systems purchased from Electrovert. Although they have automated solder-paste capability, Andover continues to rely mostly on manual board stencilling. In keeping with their philosophy of making manufacturing as simple as possible, the SMC still uses manual board stencilling. Manual stencilling is especially practical because the bottleneck on the shop floor continues to be the Fuji pick-and-place machines. Similar to stencilling, many boards are still manually separated. A computer numerical control (CNC) router is used to separate certain high volume boards. As with the rest of Andover's operations, test equipment is kept simple using custom-built fixtures for each board and "pin-tests" for electrical connections. While the in-circuit tests are the same for each board, unique pin-test fixtures are used for each of the 250 different types of boards ASMC makes.

Unexpected Problems. The only major unexpected problems occurred with the Prism product line. In its first year of production Prism system customer satisfaction suffered. Engineering and manufacturing incorrectly assumed that defect percentage rates for TH and SMT meant the same thing. With TH it is easy to spot an open connector and fix it, but with SMT it is not. A SMT solder junction can look good but "opens" on a pad are very hard to identify. Once Prism's new SMT boards achieved the same defect rates as the old TH boards in test runs, regular production was begun and systems were delivered to customers. Unfortunately, after a substantial number of Prism systems had been shipped, it quickly became apparent that undetected opens were slipping by into the field. Twenty-four machines were brought back from customers and all of them were found to have multiple opens. Over the next six months warranty costs soared and eventually hundreds of $200,000 systems were returned by angry customers. The entire engineering resources of the Prism team were devoted for one year to help solve all the open pad problems. At the end of the process, it became apparent that SMT defect rates need to be an order of magnitude better than TH defect rates before a product is released to customers.

The Sunrise product line, on the other hand, had far fewer problems with opens throughout its entire life cycle. While Sunrise boards were less complicated than Prism boards, lower complexity only accounts for part of the answer. The rich and continual communication between Sunrise engineering and ASMC manufacturing most likely explains the rest of their success in shipping good systems.

Performance Measures. Once the problem with "opens" was solved, the benefits of SMT met or exceeded all expectations. Cycle-time was reduced from six weeks under TH to three to four hours for SMT. Throughput time, in fact, is so good today that the ASMC guarantees next-day delivery for most orders. Yield was likewise increased from 80 percent up to 97 to 98 percent. The typical SMT PWB uses almost 50 percent less board space, allowing for either much denser boards if features increase while product size stays the same, or much smaller products if the board's functionality is unchanged. In several cases boards that formerly cost hundreds of dollars are now made for tens of dollars. For example, the mother board for Sunrise was quoted by an outside TH board fabricator for "X" dollars each and the ASMC was able to guide the redesign and produce it for almost one-fifth of the outside vendor's price.

In terms of the Sunrise product line, all major objectives were met. The new system in final form was desktop size and cost a third of high-performance models, meeting the original design objectives. Similarly for the Prism product line, after the early issues with opens, there have been no other major problems.

Conclusions

The following summarizes some of the major lessons learned at MPG's Andover location in the course of implementing and managing SMT.

Through-hole technology. Cleaning up process and component supplier problems when the company was still using the old TH technology proved invaluable before the SMT conversion. For over two years, manufacturing conducted experiments and worked with suppliers to remove interlayer shorts in boards, improve yields, remedy on-time delivery problems, and perfect solder paste and plating techniques. If variables like board and component quality had not been removed from the shop floor prior to SMT implementation, it would have been very difficult to implement the new technology. Indeed, if many of these factors were not already controlled it may have been almost impossible for Andover to solve the Prism open pad problem.

Experimentation. Manufacturing conducted numerous experiments with the new SMT technology before actually buying major pieces of equipment and setting up a dedicated assembly line. This experimentation not only allowed manufacturing to learn more about SMT before major capital expenditures were made, but also served as a way to educate other functions such as engineering on the benefits of surface mount. Purchasing its own reflow oven to help accelerate the production of trial boards was another important step. Indeed, it was only after manufacturing had produced numerous good trial boards that many other functions started to begrudgingly accept SMT.

Line management. SMT represented a technological discontinuity, and MPG's senior manufacturing management decided not to transfer the TH line managers to SMT. Manufacturing management recognized that the existing line managers were too steeped in the old batch manufacturing paradigm to quickly and smoothly make the shift to the new flow process. Indeed, even with new line managers, it proved to be very difficult to get workers to change their batch manufacturing habits into a continuous flow mind-set.

Temporary work force. If MPG had to rely only on its own internal work force, then the transition to SMT might have taken much longer. Fortunately, MPG was located in a hi-tech part of the country where major electronic manufacturers such as AT&T, Digital, Raytheon, and Wang had recently laid off numerous skilled shop-floor employees. MPG was able to draw some of this outside talent into the company on a short-term and long-term basis in order to help make the transitions from TH to SMT. These temporary workers helped smooth the changeover to SMT, and allowed the ASMC to more quickly ramp-up production rates.

Matched engineering and manufacturing goals. A major difference between the Sunrise and Prism product lines was that engineering's goals were closely aligned with manufacturing's process capabilities. There was an open and continual dialog between Sunrise engineers and manufacturing that was missing during the Prism conversion process. Notably, the Sunrise design team rejected the classic "throw it over the wall" mentality that so often separates engineering and manufacturing functions.

Worker transfers. The decision to transfer as many TH workers as possible to SMT proved to be a wise choice. A key early step in the SMT implementation project was transferring many of the best TH workers into the new surface mount centre. These workers tended to have the skills, flexibility, and enthusiasm necessary to make the new SMT process work. Transferring key workers from TH to SMT had another benefit. Although some shop-floor workers resisted change, and new hires may have ramped-up production even faster, a valuable precedent for future radical change was made. This has proven important for ASMC today. Shop-floor workers feel that since they survived going from TH to SMT they can now handle any new process changes.

Defects. Based upon the open pad problems for the Prism system, MPG developed a newfound appreciation for quality assurance in conjunction with advanced manufacturing technologies. ASMC, as a philosophy, actively tried to cease dependence on inspection and test. Instead, SPC was implemented to help ensure in-process quality. Finally, processes like the TQC teams were put into place to ensure that action was taken on quality problems as they occurred.

Focus on reducing cycle-time. Introducing the line engineer position and focusing on reduced cycle-time were important steps in unlocking the benefits of SMT. SMT allowed for phenomenally greater productivity, but also set the stage for potentially dramatic growth in WIP. By temporarily instating the line engineer position, complete with authority to move employees and other resources around, the ASMC was able to drive down cycle-times and avoid "drowning" in WIP. The line engineer position also helped educate shop-floor workers and supervisors on how to run as a flow, not a batch, operation.

Relative simplicity. Although SMT represented revolutionary change over TH manufacturing, Andover's manufacturing management insisted that whenever and wherever possible production methods be kept simple. For example, the PIM computer system extends from design engineering to manufacturing but is not electronically linked to the Fuji lines as part of computer integrated manufacturing (CIM). Manufacturing concentrated most of its resources on the physical process, instead of focusing on the information technology side of SMT board production. Similarly, manufacturing has stayed with manual stencils, where an operator can readily tell if solder paste missed a pad by looking at the stencil once it is lifted from the board, instead of introducing more process uncertainty and quality risks by going to automated stencilling. Likewise, Andover's manufacturing has resisted the temptation to introduce elaborate test equipment such as X-ray, ultrasonic wave, or infrared detection systems to catch defects after they are made. Instead, capital is invested in the best production equipment available coupled with carefully documented processes, highly trained workers, and SPC in order to make good boards from the beginning.