STRIVING FOR MANUFACTURING EXCELLENCE AT THE DENVER WORKS: A SUMMARY

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In 1985, AT&T's Denver Works initiated several programs designed to give the company a competitive edge in the private-branch exchange (PBX) business. Because Denver assembles systems to suit customers' orders, the goals of the programs were particularly challenging: reduce manufacturing costs, improve product quality, and shorten manufacturing intervals. As a base for improving all its operations, Denver implemented a computer-based material planning and control system, whose central activity was material requirements planning (MRP). Shop-floor processes and storeroom operations were evaluated, simplified, and integrated with the MRP system. Today, Denver's storerooms maintain minimal inventories, yet supply components and subassemblies to the shops exactly when needed to maintain the production schedules. New procedures speeded the flow of materials to the shops and final-assembly areas. Improved testing procedures at all stages increase manufacturing yields for circuit packs, equipment, and final systems. These improvements have reduced the manufacturing interval to 1 month.

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(continued on page 17)

Introduction

To enhance the company's position in the highly competitive PBX business, AT&T's Denver Works launched a series of ambitious programs in three phases, starting in 1985. The goals of the programs were to reduce manufacturing cost, improve product quality, and shorten Denver's manufacturing intervals. (The manufacturing interval starts with order receipt and concludes with product shipment.) These goals are highly interdependent. Manufacturing intervals cannot be shortened without improvements to a host of underlying procedural and physical processes. And, improved processes should lead to lower

Panel 1. Acronyms and Terms

APICS	American Production and Inventory Control Society
BOM	bill of materials
DFM	design for manufacturability
DIP	dual-in-line package
end item	a product sold as a completed item or repair part, or any item that is subject to a customer order or sales forecast
FAS	final-assembly sequencer
IMPAC	an AT&T-developed computer system for integrated manufacturing planning and control
IPE	integrated pull engineering
IPM	integrated pull manufacturing
JIT	just in time
MPS	master production schedule
MRP	material requirements planning
PBX	private-branch exchange
picking	process of withdrawing components from stock
pick list	a list of the components needed for products or finished goods to be shipped to a customer
pick week	week in which a particular pick list is used to withdraw components
PPM	parts per million
SPC	statistical process control
TOR	inventory turnover ratio; output (at cost) divided by average inventory (at cost)
TQC	total quality control
WIP	work in process

costs and higher quality products. If these goals were to be attained, the Denver Works needed to make dramatic improvements in all its operations.

The task was particularly daunting in light of the objectives established for the manufacturing intervals and the complexity of the products, which are assembled to customer order. When the program was launched, AT&T's Definity® System 75 telecommunications system[1]—the simpler of the two Definity systems—was assembled with about 40 circuit packs, drawn from about 25 different codes (part numbers). The remaining hardware—which consists of carriers, cables, power units, fan units, and the cabinet itself—offered customers only a few options.

To establish a base for further improvements, the first phase was devoted to the plant-wide implementation of a formal, computer-based material planning and control system. The central activity of such a system is *material requirements planning* (MRP), whose goal is to ensure that the right component or subassembly is available to comply with the schedules for completed products.

In the past, MRP systems had been implemented in the electronics assembly industry for products as complex as Denver's but, perhaps, not for products whose customer-order demand fluctuated by as much as 50 percent from week to week. At Denver, we also made some fundamental changes to the standard MRP approach.[2] These changes are among the topics discussed in the next section, which is devoted to Phase I of the project.

The second phase, launched in 1986, consisted of the introduction of fundamental improvements to the manufacturing processes for the System 75 PBX. We installed JIT/TQC systems to simplify Denver's shop-floor processes, and launched programs to improve the quality of circuit-pack testing. [JIT is *just in time*, a philosophy concerned with eliminating waste (e.g., inventory, rework, scrap, defects). TQC is *total quality control*, an approach that encompasses all phases of manufacturing and tries to ensure that no defective product is manufactured.] A later section of this paper describes the activities of Phase 2, dubbed the *shop-floor execution phase* to distinguish it from Phase I, which is called the *planning phase*.

In the third phase, which was launched in 1987, we integrated the MRP system, shop-floor execution, and storeroom operations. The result, called *integrated pull manufacturing* (IPM), is a novel solution that permits effi-

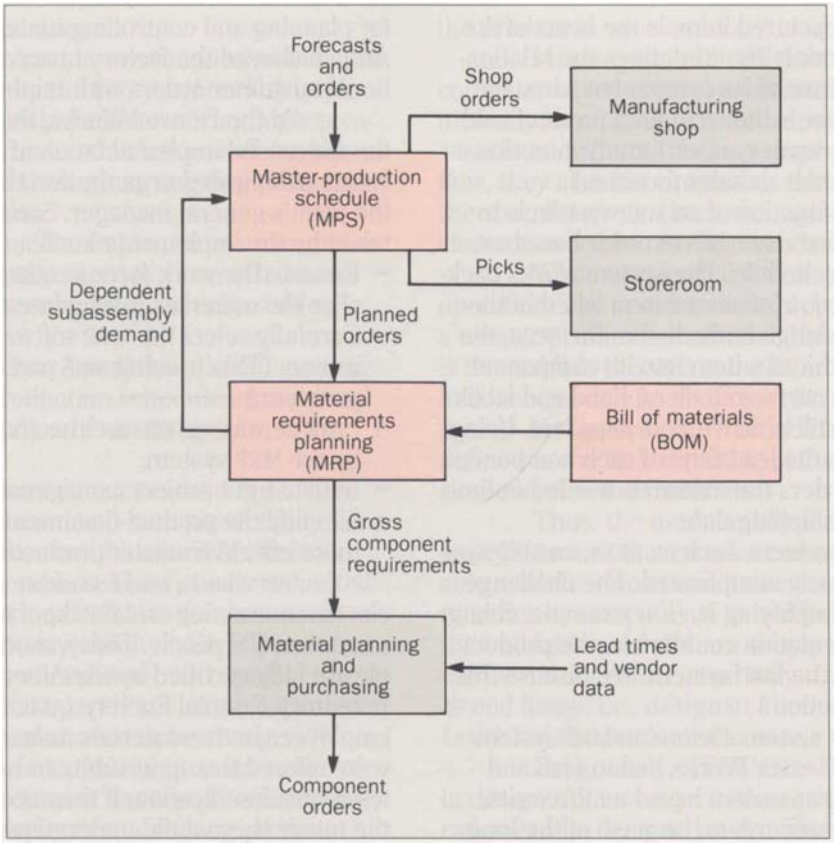

Figure 1. Basic MRP system. The MPS is a projected schedule for building an end item, while the BOM identifies the subassemblies required to build that item. To ensure parts and materials are available when needed, the MRP works backward from the end item's shipping date. Components listed in the BOM but not already on hand or on order will be ordered from suppliers to arrive just in time for the appropriate assembly step.

cient manufacturing of assembled-to-order products with many options. As we shall see, IPM resolves the apparent incompatibility between MRP, which is inherently a *push* system, and the *pull* systems that were implemented on Denver's shop floor. (In a push system, materials are ordered and released to the shop floor according to a schedule. Thus, the shop areas often must store these materials until they are really needed, or production lines must wait until materials arrive. In a pull system, materials are ordered from suppliers, including in-house assembly areas, to arrive in time to meet the shop floor's production schedule. However, they remain in the storeroom until a shop-floor request triggers their release.)

Other AT&T manufacturing facilities are also implementing IPM. In addition, some of the concepts of IPM have been applied to the product-realization process. In that environment, these concepts are called *integrated pull engineering* (IPE).

Phase 1—Material Requirements Planning

An MRP system is a formal, computer-based production and inventory management system. Figure 1 shows the key components of such a system. The master production schedule (MPS), which is a projected sched-

ule for building a manufactured item, is the heart of the system. The bill of materials (BOM) defines the relationship between an end item and its component parts and subassemblies. (*End item* is the term for a product sold as a completed item or repair part, or for any item that is subject to a customer order or sales forecast.)

A fundamental function of an MRP system is to determine when and what materials to order based on the master production schedule. The system works backward from the *shipping date* of an end item listed in the MPS. By using the knowledge embodied in the BOM, the MRP system translates the MPS item into its component elements. It checks the current stock on hand and stock previously ordered but still to arrive from suppliers. Using all this information plus the lead time of each component, the MRP system then orders the materials needed in time to meet the end item's shipping date.

For complex products, such as PBXs, an MRP system can become extremely complicated. The challenge is to arrive at ways of simplifying it. (For example, changing the product documentation could make the product appear less complex to the MRP system. We discuss this approach in the next section.)

Deploying an MRP System. Before an MRP system was implemented, the Denver Works had to plan and release materials and shop orders based on forecasts, and not on actual customer orders, because of the long lead times and long manufacturing intervals for subassemblies. End items to satisfy customer orders were then assembled from a pool of work-in-process (WIP) and finished subassemblies. However, the forecasts rarely matched the actual orders, so informal systems had been developed to expedite material to meet production schedules. This created considerable confusion in the process and greatly contributed to the factory's *hidden costs*[3] (e.g., expediting, production of the wrong items, excessive inventories).

The deployment of an MRP system created discipline and a common language for the materials management function. The MRP system also provided a tool for planning and controlling material more accurately. And, it allowed the factory to accept and plan for additional customer orders with minimal disruption.

At the Denver Works, the first step to ensure the successful implementation of an MRP system was to create a dedicated organization that reported directly to the plant's general manager. Some of the key actions taken by the implementation team were:

- Educate the work force in MRP theory, and professionalize the materials management organization.
- Carefully select the MRP software, and train people in its use. (This training was part of the MRP education program.)
- Provide ways to ensure the accuracy of data to be used by the MRP system.
- Initiate tight project management.
- Simplify the product-documentation structure to allow more effective master production scheduling.

MRP training and certification. Over 20,000 hours of classroom training on MRP theory were delivered to more than 500 people. Today, more than 50 of these people are fully certified by the American Production and Inventory Control Society (APICS). Furthermore, the employees in the materials management organization were offered the opportunity to be reclassified to a professional classification. If they accepted, and all did, in the future they would undergo periodic performance evaluations and receive salary increases based on their performance.

To strengthen the work force even more, materials management professionals from local colleges and industries were also hired by the materials management organization.

MRP software. After considering several options, including the use of a commercial software package, Denver selected an AT&T-developed MRP system called IMPAC (which stands for *integrated manufacturing planning and control*).[4] The IMPAC system was designed to deal with a product line as complex as PBXs. A generic commercial system would not have precisely matched

the needs of Denver's operations.

Data accuracy. We cannot overemphasize the need for accurate data for use by the MRP system. The implementation team's activities included ensuring high accuracy for the storeroom's on-hand balances and for bills of materials. This was done through an ongoing program of audits and corrective action.

Project management. The implementation organization provided project management to ensure that tasks were defined and that the schedules for deliverables were being met.

Product documentation. A well-thought-out strategy for generating master production schedules was critical to successful implementation of an MRP system at the Denver Works.

For assembled-to-order systems such as PBXs, an almost limitless number of end-item possibilities (i.e., systems) can be made from combinations of the basic components and subassemblies. The virtually unlimited number of end items are impossible to forecast accurately or to schedule with any validity.[5] Clearly, master scheduling at the end-item level was unacceptable.

Furthermore, if one part is specified instead of another, other parts may also need to be changed. Thus, engineering modifications could lead to a nightmare of problems. Such an environment has the potential to be error prone and not cost-effective, with long product-realization intervals because of the need for rework.

In addition, master scheduling at the end-item level for a complex system (such as System 75) ensures that the BOM would possess at least two levels. (One level is the system itself; another level would be a circuit pack that forms part of the system.) For a *weekly bucketed* MRP system, this implies that the manufacturing interval will be, at best, equivalent (in weeks) to the number of BOM levels. (A weekly bucketed system recognizes a week as the shortest unit of time.) For example, a five-level BOM in a weekly bucketed MRP system means that the manufacturing interval will be five weeks long, even though it may be physically possible to manufacture the product in two weeks.

Moreover, multilevel BOMs impose unnecessary computer-based control points and, therefore, are fundamentally incompatible with the pull process normally associated with JIT. These control points not only impede flow, they also force materials that have been released to the shop floor to go back through a physical (or logical) storeroom before moving to the next BOM level.

What was needed was a simple, single-level BOM operation. The recommended approach[2] for generating a master production schedule for high-option products is to establish the MPS at the intermediate product or buildable-module level. (For a PBX, this might be a circuit pack.) At this level, the buildable modules will be fully defined in the BOM database of the MRP system as a single-level bill of materials.

Thus, the modular bill-of-materials structure has an architecture that couples component parts to buildable modules. However, it does not link either buildable modules or components to end-item configurations. If the buildable modules are simply subassemblies, then the new architecture need only treat the subassemblies as end items; i.e., designate them as Level 0 instead of Level 1 in the product structure.

Fortunately, AT&T PBXs already were modular in design. Almost any customer-desired system configuration can be designed and manufactured from a limited set of buildable modules, using a single-level BOM. Therefore, redesign of the product was not required.

However, we needed to simplify the product documentation to make those buildable modules more visible. Details of this work were discussed by Foo et al. in an earlier issue.[6] This change made possible the complete and economical master scheduling of complex products such as System 75.

Phase II—Shop-Floor Improvements

As evidence of Denver's successful implementation of an MRP system, inventories (raw materials, parts, and subassemblies) were significantly reduced and on-

time shipments to customers improved. The next step was to improve shop-floor performance. To accomplish this, we needed to reduce the manufacturing intervals and their variances, and to improve process quality on the shop floor.

In PBX manufacture, shop-floor operations conveniently divide into three major activities:

- Circuit-pack assembly and testing. This is the most technically demanding of the activities.
- Assembly and testing of power units and fans, carriers (or shelves) that eventually will contain circuit packs, and a variety of cables. These units are commonly referred to as *equipment.*
- Final assembly and testing. This activity entails assembling the equipment into the cabinets, inserting the appropriate circuit packs into the carriers, and testing the assembled system.

The individual equipment subassemblies for the
10 PBXs are characterized by low optionality (i.e., only a few variations are available) and low demand volatility. Consequently, this area became the test bed for introducing a pull system using kanban cards.

The underlying principle of the kanban system is simple.[7-9] Kanban cards control the production at a given stage of the process and the amount of inventory (components and assembled units) between that stage and the next one. Each card represents one part or one type of part, and will serve as an *order* for the part. In a single-card kanban system, the downstream stage triggers production upstream by issuing a kanban card each time it consumes one unit of output from the upstream stage. In this way, the material is *pulled* through the process.

The number of kanban cards that link the stages is determined by the engineer who designed the production line, and controls the inventory maintained at each stage. (Fewer cards mean less inventory.) As we reduce the number of cards, the overall manufacturing interval drops if each stage can produce its output predictably. To derive continuous improvement, we gradually remove cards from the system, thereby exposing problems that might have been masked by the inventories maintained between the stages.

We implemented this now classic approach in Denver's equipment shops, thus logically integrating their operations with those of the final-assembly area. In addition, the equipment shops and final-assembly area were reconfigured into a combined equipment and final-assembly shop area. Previously, these shops had been distinct and were located in different areas of the factory. The reconfiguration helped to reduce the manufacturing interval even more. Also, the shops were integrated into a single, flexible work center, which eliminated many material-handling activities.

Circuit-Pack Manufacturing. Several efforts were underway in the circuit-pack shop, in parallel with the JIT/TQC implementations in the equipment shops.

At the start of the program, the circuit-pack manufacturing process was characterized by manufacturing intervals of 15 to 20 days, excessive work in process, large-batch manufacturing, and first-pass circuit-pack yields of only 55 percent. These were all symptoms of poor material-flow-control procedures and poor process yields.

To address these problems, three programs were launched: root-cause analysis of defects and design for manufacturability (DFM), statistical process control (SPC) and problem solving, and reengineering of procedures to improve and speed material flow.

Root-cause analysis and DFM. A small team of System 75 product developers and manufacturing engineers was formed to analyze the defects at in-circuit and system test. [For *in-circuit tests*, individual circuit packs are tested for connectivity, discrete-part values (i.e., that a specific part such as a resistor or capacitor has the value called for in the design), and some limited device functionality. A *bed of nails*, a platform of nail-like pins, is used to mate and make contact with specific parts of the circuit pack being tested. At *system test*, the configuration requested by the customer is tested.]

The team's first step was to identify the causes

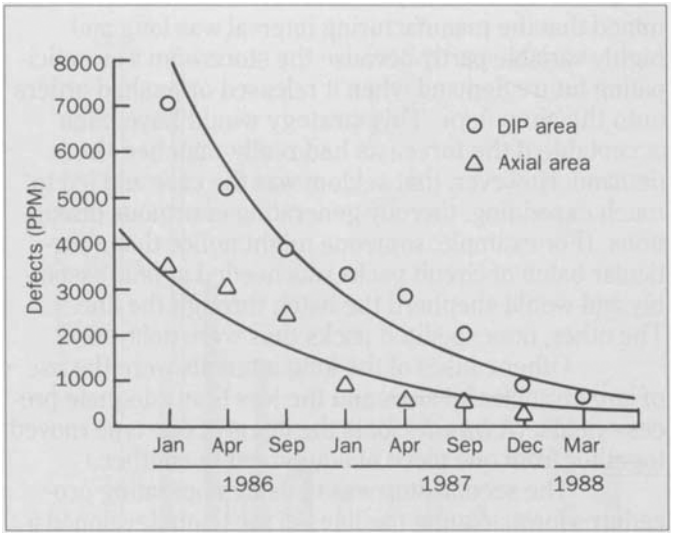

Figure 2. Improvements achieved on Denver's *orange* assembly line where DIPs and axial-lead components are inserted into circuit packs. The drop in defects represents the successful deployment of traditional SPC techniques on the shop floor.

of failure during circuit-pack test. (This test traditionally consists of two steps: the in-circuit test just described, and full-functionality test of the circuit pack.) The identification was done through data collection, Pareto analysis, and failure-mode analysis.

False indictment of components at circuit-pack test had been one of the most prominent types of failure. (*False indictment* means the test incorrectly identifies a device as having a wrong value.) The team's analysis uncovered several causes for these false indictments:

- Poorly written tests
- Inappropriate selection of acceptable device-value ranges
- Poor condition of some of the test sets.

Usually, the test operators would pass *failed* circuits, because they perceived that the pack was *good.* They had grown used to poor tests that falsely indicted certain components. Thus, testing became an art rather than a science and, consequently, was not precise.

Therefore, the team instituted a so-called *green light* test: Only those circuit packs that had been certified by the test sets as having passed were allowed to proceed to the next manufacturing step. By imposing this policy, the team improved test-set programs and eliminated the associated problems. The team then was able to address the other in-circuit test failures—the real failures. The real success at this point was the elimination of much useless work by the operators; hence, productivity rose.

System test tended to identify intermittent device failures and some device failures that could not be detected by in-circuit testing. The team's investigation led to negotiations with vendors to improve component quality, and to programs with the design organization to improve the system-test software.

Having a designer on the team proved to be vital. The designer was not only a major participant in the investigation and analysis, but was also the primary interface for feeding data and action items back to the design organizations. One of the team's outputs was the design-for-manufacturability checklist, which contains a set of DFM guidelines. Manufacturing and design organizations now use this checklist to review a design officially for manufacturability and testability before the design is released to manufacturing. A key element of the DFM review is a check to ensure that all components used in the design are on the factory's approved-parts list.

SPC and problem solving. In parallel with the quality efforts on root-cause analysis, the team started to deploy traditional SPC[10] on the shop floor. Figure 2 illustrates some of the quality improvements achieved in the component-insertion area.[11]

Material-flow procedures. As a first step to speed up the flow of material, the implementation team needed to characterize the process and identify the bottlenecks. Through data collection and analysis, the team deter-

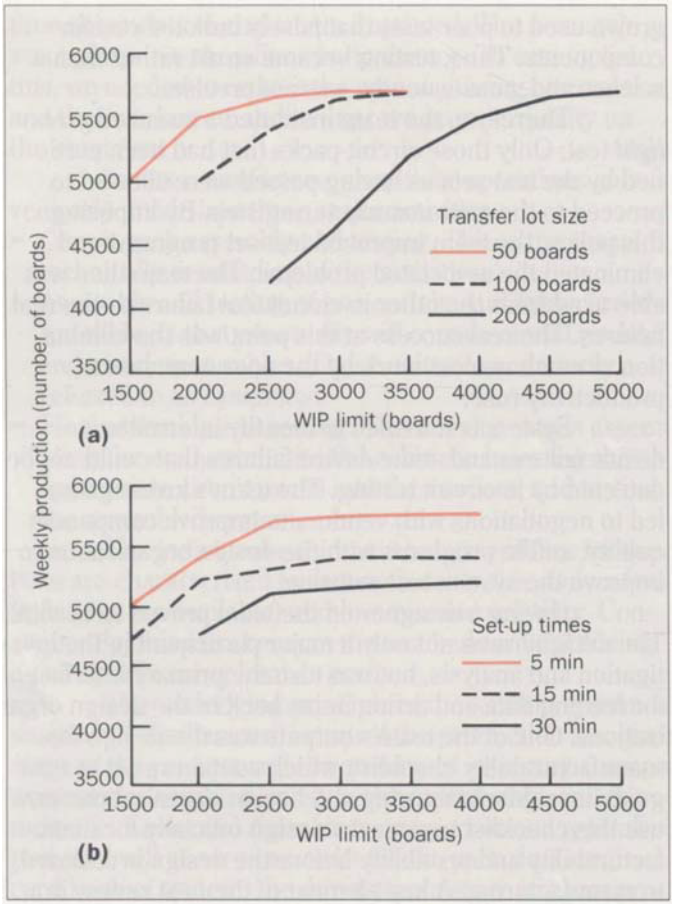

Figure 3. A simulation model was used to design operating procedures for improving the flow of material on the shop floor. Simulations suggested the optimum WIP limit for the circuit-pack shop. (a) Effects of transfer-lot size. With smaller lots, the WIP limits could be reduced without affecting production levels. A lot size of 50 permitted setting the WIP limit to 1500 circuit packs. (b) Effects of set-up time. Reducing set-up times would allow the shop to manufacture circuit packs in smaller lots.

mined that the manufacturing interval was long and highly variable partly because the storeroom was anticipating future demand when it released or pushed orders onto the shop floor. This strategy would have been acceptable if the forecasts had really matched the demand. However, that seldom was the case and led to much expediting, thereby generating enormous disruptions. (For example, someone might notice that a particular batch of circuit packs was needed at final assembly and would shepherd the batch through the line. The other, nonexpedited packs thus were delayed.)

Other causes of the long intervals were the use of large transfer-lot sizes and the less than adequate process yields. (A *transfer lot* is the items of one type moved together from one piece of equipment to another.)

The second step was to design operating procedures for managing the line, so the team developed a simulation model for the circuit-pack manufacturing line. Figure 3 shows the results of the simulation. From this model, the team determined that, if a WIP limit of 2000 circuit packs were imposed on the circuit-pack assembly line, then the manufacturing interval could be reduced by a factor of 5 to 7 without affecting production capacity. The simulation also showed (Figure 3a) that, if the transfer-lot size were reduced from 500 to 50, then the WIP limits could be reduced further to 1500 circuit packs without affecting the desired level of production.

The recommendations derived from the simulation model were implemented and proved accurate. To minimize the pain of cutting over to the new process, we initially set the WIP limits to 3000 circuit packs. When production managers became more comfortable with the new process and the process yields improved, we reduced the WIP limits, further decreasing the manufacturing interval.

Additional improvements were achieved by reducing set-up times,[11] which allowed the shop to manufacture in smaller lots. (*Set-up time* refers to the time needed to alter the machine settings to a different

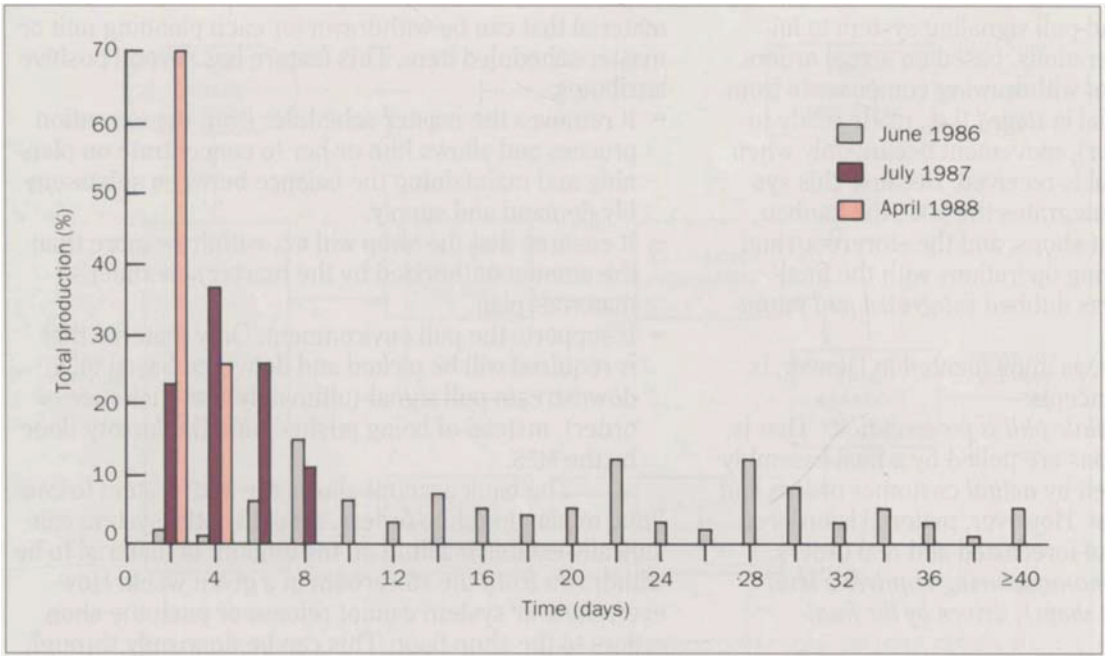

Figure 4. Assembly intervals for circuit packs on Denver's *orange* assembly line. Improved shop-floor procedures and material flow dramatically lowered the manufacturing interval and its variances. Most circuit packs are now assembled within 2 days.

circuit-pack configuration and to move in the appropriate materials.) Figure 3b shows the effect of these improvements, as suggested by the simulation model.

The facilities (equipment on the shop floor) were also reconfigured to improve the flow of materials and reduce the need for shop-floor scheduling.

Figure 4 shows the reduction in the manufacturing interval and its variance over a period of 20 months, a result of the overall implementation.

Phase III—Integrated Pull Manufacturing

At the start of Phase III, the Denver Works had reached a point where the material demands were balanced with material supplies. This was evidence that the MRP system had been successfully implemented and that the shop floor was operating efficiently as a result of the JIT/TQC programs.

However, the various factory operations still were not fully integrated. To minimize—at the lowest cost—the total interval for manufacturing the systems, all operations had to be synchronized. Also, we needed a way to marry planning, embodied in the MRP system, with the shop-floor execution procedures that operated in a pull mode.

The problems lay primarily in circuit-pack manufacturing. Unlike the equipment subassemblies, which consist of a limited set of codes, Denver's full product line embraced several hundred unique circuit-pack codes. Although System 75 itself required only about 25 distinct circuit-pack codes, in the long run, Denver needed a solution that could handle all its circuit packs.

The solution, which is described in the paper by Doshi and Krupka,[12] is a hybrid system that combines both the MRP and pull approaches.[13,14] It consists of a

forward-looking, demand-pull signaling system to initiate storeroom *pick* operations, based on actual orders. (*Picking* is the process of withdrawing components from stock.) After the material is *staged* (i.e., made ready to move onto the shop floor), movement occurs only when a downstream pull signal is received. Because this system synchronizes and integrates the MRP, the kanban system in the equipment shops, and the storeroom and circuit-pack manufacturing operations with the final-assembly schedule, it was dubbed *integrated pull manufacturing* or IPM.

The IPM system, as implemented in Denver, is based on two critical concepts:

- *MRP is for planning, while pull is for execution.* That is, all shop-floor operations are pulled by a final-assembly sequence that is driven by *actual* customer orders and not by an MPS forecast. However, material is ordered using a combination of forecasted and real orders.
- *Smooth and efficient manufacturing requires a level load on resources (the shops), driven by the final-assembly schedule.*

MRP for Planning, Pull for Execution. In general, the use of MRP II systems (in particular, automated shop-floor control systems) to schedule or push shop orders onto the shop floor and then to micromanage has led to disappointing results. (MRP II implies controlling shop-floor operations, while MRP is concerned only with the planning phase. *Micromanaging* implies an attempt to push material along the factory floor according to a predetermined schedule, rather than letting the material be pulled "naturally" through the line.)

We decided that MRP should be used for planning, but a pull system should be used for execution. The key to this separation was the development of a *bank-account* feature in the MRP system. (For the discussion that follows, we will use *master scheduler* to refer to the person responsible for the master schedules.)

The bank-account feature permits the master scheduler to deposit or authorize a maximum level of material that can be withdrawn for each planning unit or master-scheduled item. This feature has several positive attributes:

- It removes the master scheduler from the execution process and allows him or her to concentrate on planning and maintaining the balance between subassembly demand and supply.
- It ensures that the shop will not withdraw more than the amount authorized by the master scheduler's materials plan.
- It supports the pull environment. Only material that is required will be picked and delivered based on a downstream pull signal (ultimately, the customer order), instead of being pushed onto the factory floor by the MPS.

The bank account allows the MRP system to continue to plan for shop orders. Also, the MRP system can logically establish a limit on the amount of material to be withdrawn from the storeroom in a given week. However, the MRP system cannot release or push the shop orders to the shop floor. This can be done only through a pull signal from the IPM system.

Level Load. We have just described how an MRP or push system can be integrated with pull execution. However, to achieve a short interval at the lowest cost, it is important to ensure that as level a load as possible be imposed on the manufacturing resources. This observation follows from queueing theory,[15] which tells us: For a given load, the manufacturing interval increases with the variability in the system.

Fortunately, the systems scheduled for shipment in a given week may be completed any day during that week. Because these systems are custom built and differ in composition, we can shuffle their completion dates to impose a level load on the subassembly shops.

The mathematical approach to this sequencing problem is described in the paper by Luss, Rosenwein, and Wahls.[16] Their algorithm—embodied in a program called the *final-assembly sequencer* (FAS)—consists of an

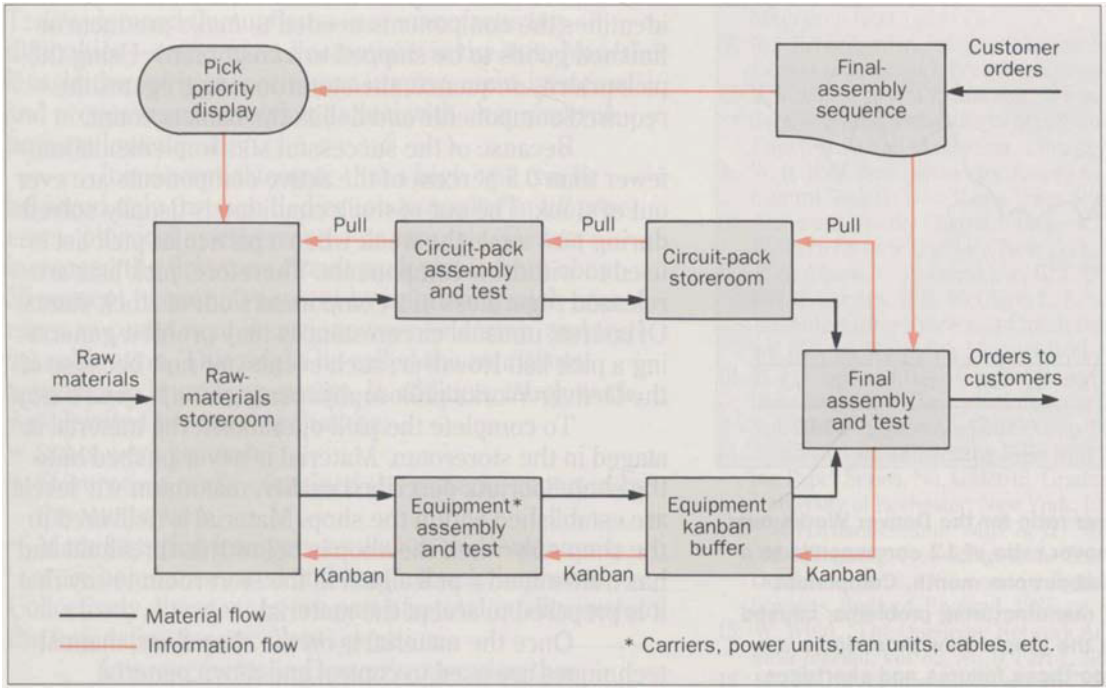

Figure 5. The IPM operations architecture includes MRP for planning and scheduling, and pull execution for getting material onto the shop floor. IPM determines when materials should be withdrawn from the storeroom and when assembly of circuit packs should start. Based on the final-assembly sequence (the output from FAS), subassemblies are pulled from the shops into the final-assembly area via a manual kanban system.

efficient search that is based on interchanges of systems.

IPM Process. Figure 5 shows the overall manufacturing architecture, including the MRP planning and pull execution. Each month, the product management and manufacturing organizations produce a forecast of demand. Because the production plan is based partly on a forecast, the precise configurations are not known. Consequently, we need to estimate the demand for material using recent configurations, which are called *typicals*. These materials requirements are translated into the buildable items that populate the master production schedule. Then, using the master production schedule, the materials management organization releases purchase orders to vendors for raw materials and components.

The IPM process begins when the Denver Works order-processing system receives orders from customers for PBX systems. This software system then converts customer requirements into configurations. Each night, the list of configurations is translated into *planning-unit* demands, which are then transferred to the MRP system. The MRP system displays the demands on the master-production-scheduling grid (a computer screen), based on the scheduled shipping dates for the customer orders.

IPM uses a demand generator that consists of the FAS program and a net-circuit-pack requirements module. By using its sequencing algorithm, the FAS program processes the weekly demand for cabinets into daily requirements for the final-assembly shop. The objective is to generate the smoothest load on the feeder shops. Input comes from the customer-order database. Based on the final-assembly sequence (the output from FAS), equipment shop subassemblies are pulled into final

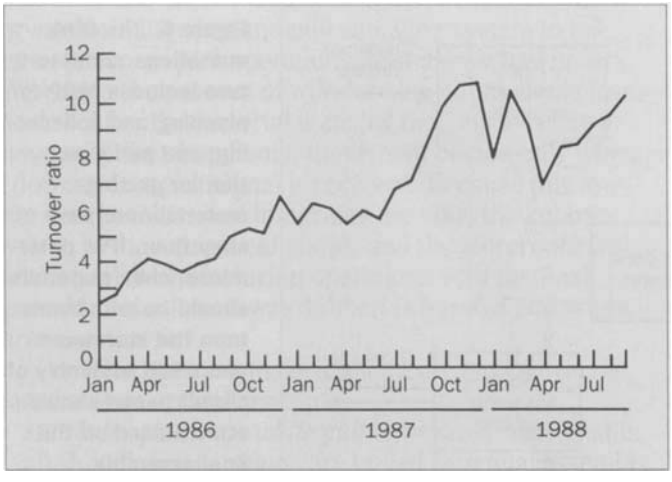

Figure 6. Inventory turnover ratio for the Denver Works over a 20-month period. A turnover ratio of 12 corresponds to a manufacturing interval of about one month. Component failures or shortages, not manufacturing problems, caused the recent fluctuations in the graph. New procedures are being installed to eliminate these failures and shortages.

assembly via a manual kanban system.

For the circuit packs, FAS translates the end-item requirements into circuit-pack requirements. IPM determines the net-circuit-pack requirements based on the WIP information contained in the master production schedule for circuit packs. Then, the manufacturing lead times for the circuit packs are used to determine when to start manufacturing the packs. Using this calculation, IPM generates a priority list of starts for the circuit packs.

The manufacturing process begins in the storeroom. A pick-priority listing that IPM generates defines a storeroom-pick order. However, before an order can be picked, material must have been deposited in the bank account. The master scheduler is responsible for establishing the bank-account level by logically depositing pick lists into the storeroom bank account. (A *pick list* identifies the components needed to make products or finished goods to be shipped to a customer.) Using the pick-priority sequence, the storeroom aggregates the required components and debits the bank account.

Because of the successful MRP implementation, fewer than 0.5 percent of the active components are ever out of stock. The out-of-stock condition is usually solved during *pick week*, the week when a particular pick list is used to withdraw components. Therefore, pick lists are released regardless of a component's out-of-stock status. Of course, unusual circumstances may prohibit generating a pick list. However, such events are rare because of the Denver Works philosophy: *never give up—find a way!*

To complete the pick operations, the material is staged in the storeroom. Material is never pushed onto the shop floor. As described earlier, maximum WIP levels are established within the shop. Material is delivered to the shop only when the shop is below this threshold and has transmitted a pull signal to the storeroom to say that it is prepared to accept the material.

Once the material is on the shop floor, manual techniques are used to control and move material between work areas in a first-in, first-out way and into the final-assembly area. Because of the short manufacturing interval, Denver does not require a computer-based shop-floor control or materials-tracking system. Completed circuit packs are delivered to a circuit-pack buffer at the final-assembly area.

Results

The best measure of the overall system's performance is the inventory turnover ratio (TOR), which is defined as output (at cost) divided by average inventory (at cost). Figure 6 shows the performance for the Denver Works over a 20-month period.

As a point of reference, a TOR of 12 corresponds to a manufacturing interval of about one month. This implies that, on the average, raw material received by Denver is shipped one month later as a finished product.

Today, demand fluctuations—not manufacturing difficulties—cause most fluctuations in the TOR. Nonetheless, in the spirit of continuous improvement, systems and processes are evolving to deal with changing volumes at lower cost.

It is essential to note that a high TOR can be achieved only through dedication to quality in *all* processes, physical or otherwise. For example, Denver increased the first-pass circuit-pack yields from about 55 percent to over 90 percent by improving such processes as component insertion, wave soldering, and test-set calibration. This might be called the *traditional* approach to improving quality. In addition, much work was devoted to ensuring that the:

- BOMs were accurate.
- Storerooms really contained the material reported by the MRP system.
- Manufacturing intervals, as well as their variances, were being measured and continuously improved.

Collectively, these steps are part of a total quality system, the foundation for excellent operations.

Improvements in Denver's operation thus depend on the introduction of a few key concepts, coupled with scrupulous attention to detail and dedication to continuous improvement.

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Biographies (continued)

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