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13

Production and Manufacturing

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13.1 Types of Manufacturing

Richard J. Schonberger

Although there are many ways to categorize manufacturing, three general categories stand out. These three (which probably have emerged from production planning and control lines of thought) are

1. **Job-shop production.** A job shop produces in small lots or batches.
2. **Mass production.** Mass production involves machines or assembly lines that manufacture discrete units repetitively.
3. **Continuous production.** The **process industries** produce in a continuous flow.

Primary differences among the three types center on output volume and variety and **process** flexibility. Table 13.1 matches these characteristics with the types of manufacturing and gives examples of each type. The following discussion begins by elaborating on Table 13.1. Next are comments on hybrid and uncertain types of manufacturing. Finally, five secondary characteristics of the three manufacturing types are presented.

TABLE 13.1 Types of Manufacturing — Characteristics and Examples

Volume Variety Flexibility	Very low Highest Highest	High Low Low	Highest Lowest Lowest
1. Job-shop production	Tool and die making Casting (foundry) Baking (bakery)		
2. Mass production		Auto assembly Bottling Apparel manufacturing	
3. Continuous production			Paper milling Refining Extrusion

Job-Shop and Batch Production

As Table 13.1 shows, job-shop manufacturing is very low in volume but is highest in output variety and process flexibility. In this mode, the processes — a set of resources including labor and equipment — are reset intermittently to make a variety of products. (Product variety requires flexibility to frequently reset the process.)

In tool and die making, the first example, the volume is generally one unit, for example, a single die set or mold. Since every job is different, output variety is at a maximum, and operators continually reset the equipment for the next job.

Casting in a foundry has the same characteristics, except that the volume is sometimes more than one, that is, a given job order may be to cast one, five, ten, or more pieces. The multipiece jobs are sometimes called lots or **batches**.

A bakery makes a variety of products, each requiring a new series of steps to set up the process, for example, mixing and baking a batch of sourdough bread, followed by a batch of cinnamon rolls.

Mass Production

Second in Table 13.1 is mass production. Output volume, in discrete units, is high. Product variety is low, entailing low flexibility to reset the process.

Mass production of automobiles is an example. A typical automobile plant will assemble two or three hundred thousand cars a year. In some plants, just one model is made per assembly line; variety is low (except for option packages). In other plants, assembly lines produce mixed models. Still, this is considered mass production since assembly continues without interruption for model changes.

In bottling, volumes are much higher, sometimes in the millions per year. Changing from one bottled product to another requires a line stoppage, but between **changeovers** production volumes are high (e.g., thousands). Flexibility, such as changing from small to large bottles, is low; more commonly, large and small bottles are filled on different lines.

Similarly, mass production of apparel can employ production lines, with stoppages for pattern changes. More conventionally, the industry has used a very different version of mass production: cutters, sewers, and others in separate departments each work independently, and material handlers move components from department to department to completion. Thus, existence of an assembly line or production line is not a necessary characteristic of mass production.

Continuous Production

Products that flow — liquids, gases, powders, grains, and slurries — are continuously produced, the third type in Table 13.1. In continuous process plants, product volumes are very high (relative to, for example, a job-shop method of making the same product). Because of designed-in process limitations (pumps, pipes, valves, etc.), product variety and process flexibility are very low.

In a paper mill, a meshed belt begins pulp on its journey though a high-speed multistage paper-making machine. The last stage puts the paper on reels holding thousands of linear meters. Since a major product changeover can take hours, plants often limit themselves to incremental product changes. Special-purpose equipment design also poses limitations. For example, a tissue machine cannot produce newsprint, and a newsprint machine cannot produce stationery. Thus, in paper making, flexibility and product variety for a given machine are very low.

Whereas a paper mill produces a solid product, a refinery keeps the substance in a liquid (or sometimes gaseous) state. Continuous refining of fats, for example, involves centrifuging to remove undesirable properties to yield industrial or food oils. As in paper making, specialized equipment design and lengthy product changeovers (including cleaning of pipes, tanks, and vessels) limit process flexibility; product volumes between changeovers are very high, sometimes filling multiple massive tanks in a tank farm.

Extrusion, the third example of continuous processing in Table 13.1, yields such products as polyvinyl chloride pipe, polyethylene film, and reels of wire. High process speeds produce high product volumes, such as multiple racks of pipe, rolls of film, or reels of wire per day. Stoppages for changing extrusion heads and many other adjustments limit process flexibility and lead to long production runs between changeovers. Equipment limitations (e.g., physical dimensions of equipment components) keep product variety low.

Mixtures and Gray Areas

Many plants contain a mixture of manufacturing types. A prominent example can be found in the process industries, where production usually is only partially continuous. Batch mixing of pulp, fats, or plastic granules precedes continuous paper making, refining of oils, and extrusion of pipe. Further processing may be in the job-shop mode: slitting and length-cutting paper to customer order, secondary mixing and drumming of basic oils to order, and length cutting and packing of pipe to order.

Mixed production also often occurs in mass production factories. An assembly line (e.g., assembling cars or trucks) may be fed by parts, such as axles, machined in the job-shop mode from castings that are also job-shop produced. Uniform mass-made products (e.g., molded plastic hard hats) may go to storage where they await a customer order for final finishing (e.g., decals) in the job-shop mode. An apparel plant may mass produce sportswear on one hand and produce custom uniforms for professional sports figures in the job-shop mode on the other.

More than one type of manufacturing in the same plant requires more than one type of production planning, scheduling, and production. The added complexity in management may be offset, however, by demand-side advantages of offering a fuller range of products.

Sometimes, a manufacturing process does not fit neatly into one of the three basic categories. One gray area occurs between mass production and continuous production. Some very small products — screws, nuts, paper clips, and toothpicks — are made in discrete units. However, because of small size, high volumes, and uniformity of output, production may be scheduled and controlled not in discrete units but by volume, thus approximating continuous manufacturing. Production of cookies, crackers, potato chips, and candy resembles continuous forming or extrusion of sheet stock on wide belts, except that the process includes die cutting or other separation into discrete units, like mass production. Link sausages are physically continuous, but links are countable in whole units.

Another common gray area is between mass and job-shop production. A notable example is high-volume production of highly configured products made to order. Products made for industrial uses — such as specialty motors, pumps, hydraulics, controllers, test equipment, and work tables — are usually made in volumes that would qualify as mass production, except that end-product variety is high, not low.

These types of manufacturing with unclear categories do not necessarily create extra complexity in production planning and control. The difficulty and ambiguity are mainly terminological.

Capital Investment, Automation, Advanced Technology, Skills, and Layout

The three characteristics used to categorize manufacturing — volume, variety, and flexibility — are dominant but not exhaustive. To some extent, the manufacturing categories also differ with respect to capital investment, technology, skills, and layout.

Typically, continuous production is highly capital intensive, whereas mass production is often labor intensive. The trend toward automated, robotic assembly, however, is more capital intensive and less labor intensive, which erodes the distinction. Job-shop production on conventional machines is intermediate as to capital investment and labor intensiveness. However, computer numerically controlled machines and related advanced technology in the job shop erodes this distinction as well.

As technology distinctions blur, so do skill levels of factory operatives. In conventional high-volume assembly, skill levels are relatively low, whereas those of machine operators in job shops — such as machinists and welders — tend to be high. In automated assembly, skill levels of employees tending the production lines elevate toward technician levels — more like machinists and welders. In continuous production skill levels range widely — from low-skilled carton handlers and magazine fillers to highly skilled process technicians and troubleshooters.

Layout of equipment and related resources is also becoming less of a distinction than it once was. The classical job shop is laid out by type of equipment: all milling machines in one area, all grinding machines in another. Mass and continuous production have been laid out by the way the product flows: serially and linearly. Many job shops, however, have been converted to cellular layouts — groupings of diverse machines that produce a family of similar products. In most work cells the flow pattern is serial from machine to machine, but the shape of the cell is not linear; it is U-shaped or, for some larger cells, serpentine. Compact U and serpentine shapes are thought to provide advantages in teamwork, material handling, and labor flexibility.

To some degree, such thinking has carried over to mass production, that is, the trend is to lay out assembly and production lines in U and serpentine shapes instead of straight lines, which was the nearly universal practice in the past. In continuous production of fluids, the tendency has always been toward compact facilities interconnected by serpentine networks of pipes. Continuous production of solid and semisolid products (wide sheets, extrusions, etc.), on the other hand, generally must move in straight lines, in view of the technical difficulties in making direction changes.

Defining Terms

Batch: A quantity (a lot) of a single item.

Changeover (setup): Setting up or resetting a process (equipment) for a new product or batch.

Continuous production: Perpetual production of goods that flow and are measured by area or volume; usually very high in product volume, very low in product variety, and very low in process flexibility.

Job-shop production: Intermittent production with frequent resetting of the process for a different product or batch; usually low in product volume, high in product variety, and high in process flexibility.

Mass production: Repetitive production of discrete units on an assembly line or production line; usually high in product volume, low in product variety, and low in process flexibility.

Process: A set of resources and procedures that produces a definable product (or service).

Process industry: Manufacturing sector involved in continuous production.

Further Information

Industrial Engineering. Published monthly by the Institute of Industrial Engineers.

Manufacturing Engineering. Published monthly by the Society of Manufacturing Engineers.

Schonberger, R. J. and Knod, E. M. *Operations Management: Customer-Focused Principles, 6th ed.*, Richard D. Irwin, Burr Ridge, IL, 1997; see, especially, chapters 12, 13, 14, and 15.

13.2 Management and Scheduling

Edward M. Knod, Jr.

Prescriptions for how managers ought to establish and maintain world-class excellence in their organizations changed substantially during the 1980s and 1990s. Emerging markets, shifting patterns of global competitiveness and regional dominance in key industries, the spread of what might be called Japanese management and manufacturing technologies, and the philosophy and tools of the total quality movement are among the factors that combined to usher in a heightened focus on the overall capacity required to provide continuous improvement in meeting evolving customer needs. The effects of this contemporary management approach first appeared in manufacturing [Schonberger, 1982; Hall, 1983] and continue to have profound influence in that sector. Changes in the way managers approach scheduling serve to exemplify the new thinking.

This section begins with an overview of contemporary management, continues with a discussion of scheduling in various manufacturing environments, and concludes with references and suggested sources of additional information.

Management: Definition and Innovations

In a somewhat general-to-specific progression, **management** in contemporary competitive manufacturing organizations may be described by (1) duties and activities, (2) requisite skills and attributes, (3) trends and innovations, and (4) principles for managing operations.

Duties and Activities

Briefly, the goal of management is to ensure organizational success in the creation and delivery of goods and services. Popular definitions of management often employ lists of activities that describe what managers do. Each activity serves one or more of three general, and overlapping, duties: creating, implementing, and improving.

- Creating. Activities such as planning, designing, staffing, budgeting, and organizing accomplish the creativity required to build and maintain customer-serving capacity. Product and **process** design, facility planning and layout, work-force acquisition and training, and materials and component sourcing are among the tasks that have a substantial creative component.
- Implementing. When managers authorize, allocate, assign, schedule, or direct, emphasis shifts from creating to implementing — putting a plan into action. (A frequent observation is that the biggest obstacle to successful implementation is lack of commitment.) During implementation, managers also perform controlling activities, that is, they monitor performance and make necessary adjustments.
- Improving. Environmental changes (e.g., new or revised customer demands, challenges from competitors, and social and regulatory pressures) necessitate improvements in output goods and services. In response to — or better yet, in anticipation of — those changes, managers re-create, that is, they start the cycle again with revised plans, better designs, new budgets, and so forth.

Outcomes, desirable or otherwise, stem from these activities. A goal-oriented manager might describe the aim of the job as "increased market share" or "greater profitability", but he or she will try to attain that goal by creating, implementing, and improving.

Requisite Skills and Attributes

Exact requirements are difficult to pin down, but any skill or attribute that helps a manager make better decisions is desirable. Bateman and Zeithaml [1993] suggest that managers need technical skills, interpersonal and communications skills, and conceptual and decision skills. Extension of these broad categories into job-specific lists is perhaps unwarranted given current emphasis on cross-functional career migration and assignments to interdisciplinary project teams or product groups. Sound business acumen and personal traits such as demeanor, good time-management habits, and pleasant personality, however, are general attributes that serve managers in any job. More recently, emphasis on computer (and information system) literacy and knowledge of foreign languages and customs has increased as well.

Trends and Innovations

An array of publications, seminars, and other vehicles for disseminating "how and why" advice has bolstered the spread of contemporary management theory and research. Manufacturing managers constitute the primary target audience for much of this work. The information bounty can be reduced, tentatively, to a set of core trends and innovative approaches. Table 13.2 offers a short list of seven concept areas within which numerous interrelated trends or innovations have emerged. They are dominant themes in contemporary management literature and in that regard help define what today's managers are all about.

TABLE 13.2 Trends and Innovations in Management

Customers at center stage. The customer is the next person or process — the destination of one's work. The provider-customer chain extends, process to process, on to final consumers. Whatever a firm produces, customers would like it to be better, faster, and cheaper; product managers therefore embrace procedures that provide *total quality, quick responses,* and *waste-free* (economical) *operations.* These three aims are mutually supportive and form the core rationale for many of the new principles that guide managers.

Focus on improvement. Managers have a duty to embrace improvement. A central theme of the TQ movement is constant improvement in output goods and services and in the processes that provide them. Sweeping change over the short run, exemplified by business process reengineering [Hammer and Champy, 1993], anchors one end of the improvement continuum; the rationale is to discard unsalvageable processes and start over so as not to waste resources in fruitless repair efforts. The continuum's other end is described as incremental continuous improvement and is employed to fine tune already-sound processes for even better results.

Revised "laws" of economics. Examples of the contemporary logic include the following. Quality costs less, not more. Costs should be allocated to the activities that cause their occurrence. Prevention (of errors) is more cost-effective than discovery and rework. Training is an investment rather than an expense. Value counts more than price (e.g., in purchasing). Desired market price should define (target) manufacturing cost, not the reverse.

Elimination of wastes. Waste is anything that doesn't add value; it adds cost, however, and should be eliminated. Waste detection begins with two questions: "Are we doing the right things?" and "Are we doing those things in the right way?" Toyota identifies seven general categories of wastes [Suzaki, 1987], each with several subcategories. Schonberger [1990] adds opportunities for further waste reduction by broadening the targets to include nonobvious wastes. Simplification or elimination of indirect and support activities (e.g., production planning, scheduling, and control activities; inventory control; costing and reporting; etc.) is a prime arena for contemporary waste-reduction programs (Steudel and Desruelle, 1992].

Quick-response techniques. Just-in-time (JIT) management, queue limiters, reduced setups, better maintenance, operator-led problem solving, and other procedures increase the velocity of material flows, reduce throughput times, and eliminate the need for many interdepartmental control transactions. Less tracking and reporting (which add no value) reduces overhead. Collectively, quick-response programs directly support faster customer service [Blackburn, 1991].

The process approach. The process approach has several advantages [Schonberger and Knod, 1994]. Processes cut across functional departments; attention is drawn to overall or group results, ideally by a cross-functional team that may also include customers and suppliers. Processes are studied at the job or task level, or at the more detailed operations level. Automation can be beneficial *after* process waste is removed, and further reduction in variation is needed. Tools for measurement and data analysis, methods improvement, and team building are among those needed for successful process improvement.

Human resources management. Increased reliance on self-directed teams (e.g., in cells or product groups) and/or on-line operators for assumption of a larger share of traditional management responsibilities is a product of the management revolution of the 1980s that had noticeable impact in the 1990s. Generally, line or shop employees have favored those changes; they get more control over their workplaces. There is a flip side: as employee empowerment shifts decision-making authority, as JIT reduces the need for many reporting and control activities, and as certain supervisory and support-staff jobs are judged to be non-value adding, many organizations downsize. Lower- and mid-level managers and support staff often bear the job-loss burden.

Principles for Managing Operations

The final and most detailed component of this general-to-specific look at contemporary management is a set of action-oriented, prescriptive principles for managing operations in any organization (see Table 13.3). The principles apply to managers at any level and define ways for increasing competitiveness in manufacturing organizations. Brief supporting rationale and techniques or procedures that exemplify each principle appear in the right-hand columns; Schonberger and Knod [1994] provide a more detailed discussion.

Scheduling

Basically, **scheduling** refers to the activities through which managers allocate capacity for the near future. It includes the assignment of work to resources, or vice versa, and the determination of timing for specific work elements and thus answers the questions "who will do what" and "when will they do it". In manufacturing, the scheduling time horizon is usually weekly, daily, or even hourly. In general, scheduling

TABLE 13.3 Principles for Managing Operations

Principle	Rationale and Examples
Get to know customers; team up to form partnerships and share process knowledge.	Providers are responsible for getting to know their customers' processes and operations. By so doing, they offer better and faster service, perhaps as a member of customers' teams.
Become dedicated to rapid and continual increases in quality, flexibility, and service and decreases in costs, response or lead time, and variation from target.	The logic of continuous improvement, or *kaizen* [Imai, 1986], rejects the "if it ain't broke..." philosophy; seeks discovery and then prevention of current potential problems; and anticipates new or next-level standards of excellence.
Achieve unified purpose through shared information and cross-functional teams for planning/design, implementation, and improvement efforts.	Information sharing keeps all parties informed. Early manufacturing/supplier involvement and concurrent or simultaneous product and process design are components of the general cross-functional team design concept.
Get to know the competition and world-class leaders.	Benchmarking [Camp, 1989] elevates the older notion of "reverse engineering" to a more formal yet efficient means of keeping up with technology and anticipating what competitors might do. Search for best practices.
Cut the number of products (e.g., types or models), components, or operations; reduce supplier base to a few good ones and form strong relationships with them.	Product line trimming removes nonperformers; component reduction cuts lead times by promoting simplification and streamlining. Supplier certifications and registrations (e.g., ISO 9000) lend confidence, allow closer partnering with few suppliers (e.g., via EDI), and reduce overall buying costs.
Organize resources into multiple chains of customers, each focused on a family of products or services; create cells, flow lines, plants in a plant.	Traditional functional organization by departments increases throughput times, inhibits information flow, and can lead to "turf battles". Flow lines and cells promote focus, aid scheduling, and employ cross-functional expertise.
Continually invest in human resources through cross-training for mastery of multiple skills, education, job and career path rotation, health and safety, and security.	Employee involvement programs, team-based activities, and decentralized decision responsibility depend on top-quality human resources. Cross-training and education are keys to competitiveness. Scheduling — indeed, all capacity management — is easier when the work force is flexible.
Maintain and improve present equipment and human work before acquiring new equipment, then automate incrementally when process variability cannot otherwise be reduced.	*TPM*, total productive maintenance [Nakajima, 1988], helps keep resources in a ready state and facilitates scheduling by decreasing unplanned downtime, thus increasing capacity. Also, process improvements must precede automation; get rid of wasteful steps or dubious processes first.
Look for simple, flexible, movable, and low-cost equipment that can be acquired in multiple copies — each assignable to a focused cell, flow line, or plant-in-a-plant.	Larger, faster, general-purpose equipment can detract from responsive customer service, especially over the longer run. A single fast process is not necessarily divisible across multiple customer needs. Simple, dedicated equipment is an economical solution; setup elimination is an added benefit.
Make is easier to make/provide goods and services without error or process variation.	The aim is to prevent problems or defects from occurring — the fail-safing (*pokayoke*) idea — rather than rely on elaborate control systems for error detection and the ensuing rework. Strive to do it right the first time, every time.
Cut cycle times, flow time, distance, and inventory all along the chain of customers.	Time compression provides competitive advantage [Blackburn, 1991]. Removal of excess distance and inventory aids quick response to customers. Less inventory also permits quicker detection and correction of process problems.
Cut setup, changeover, get-ready, and startup times.	Setup (or changeover) time had been the standard excuse for large-lot operations prior to directed attention at reduction of these time-consuming activities [Shingo, 1985]. Mixed-model processing demands quick changeovers.
Operate at the customer's rate of use (or a smoothed representation of it); decrease cycle interval and lot size.	Pull-mode operations put the customer in charge and help identify bottlenecks. Aim to synchronize production to meet period-by-period demand rather than rely on large lots and long cycle intervals.
Record and *own* quality, process, and problem data at the workplace.	When employees are empowered to make decisions and solve problems, they need appropriate tools and process data. Transfer of point-of-problem data away from operators and to back-office staff inhibits responsive, operator-centered cures.
Ensure that front-line associates get first chance at problem solving — before staff experts.	Ongoing process problems and on-the-spot emergencies are most effectively solved by teams of front-line associates; staff personnel are best used in advisory roles and for especially tough problems.

TABLE 13.3 (continued) Principles for Managing Operations

Principle	Rationale and Examples
Cut transaction and reporting; control *causes*, not symptoms.	Transactions and reports often address problem symptoms (e.g., time or cost variances) and delay action. Quick-response teams, using data-driven logic, directly attack problem causes and eliminate the need for expensive reporting.

Source: Schonberger, R. J. and Knod, E. M., Jr. *Operations Management: Continuous Improvement, 5th ed.*, chapter 1, Richard D. Irwin, Burr Ridge, IL, 1994. Adapted with permission.

(1) flows from and is related to planning, (2) is determined by manufacturing environment, and (3) can be simplified when appropriate management principles are followed.

Relationship to Planning

The planning activity also answers the "who", "what", and "when" questions, but in more general or aggregate terms for the longer time horizon — typically months, quarters, or years into the future. So, in the temporal sense, scheduling is short-term planning. However, planning involves more. With the other creative activities, planning also addresses the characteristics of what is to be done (e.g., designs), quantity and variety (e.g., the product mix), how work will be accomplished (e.g., methods and procedures), utilization of funds (e.g., budgeting), and so on — including how scheduling itself will be accomplished. When planning (or design) has been thorough and things go according to plan, little creativity should be required in scheduling; it ought to be mostly an implementation activity.

In manufacturing, aggregate demand forecasts are filtered by business plans and strategies — what the company wants to do — to arrive at aggregate capacity and production plans. The master schedule states what the company plans to provide, in what quantities, and when. To the extent that on-hand or previously scheduled inventories are insufficient to meet the commitments described by the master schedule, additional purchasing and production are required. Consequently, detailed planning and scheduling activities — for fabrication of components and subassemblies and for final assembly operations — come into play. Scheduling is among the production activity control duties that form the "back end" of the total manufacturing planning and control system [Vollmann et al., 1992]. Thus, it might be said that scheduling flows from planning.

Effects of Manufacturing Environment

The type of manufacturing environment determines the nature of scheduling, as shown in Table 13.4. As the table notes, project and repetitive/continuous environments present less extreme scheduling problems; the sources listed at the end of this section contain suitable discussion. For project scheduling, see Evans [1993], Kerzner [1989], and Schonberger and Knod [1994]. For scheduling in repetitive or continuous production, see Schniederjans [1993] and Schonberger and Knod [1994].

The variables inherent with traditional batch and job environments create the most complex scheduling (and control) problems. *Loading* (allocation of jobs to work centers), *sequencing* (determining job-processing order), *dispatching* (releasing jobs into work centers), *expediting* (rushing "hot" jobs along), and *reporting* (tracking job progress along routes) are among the specific activities. *Assignment models* can be of assistance in loading, and *priority rules* may be used for sequencing and dispatching. In batch operations, *lot splitting* and *overlapping* may help expedite urgent jobs. Unfortunately, however, throughput time in many job operations consists largely of queue time, setup time, move time, and other non–value-adding events. Perhaps even more unfortunate have been managers' attempts to "solve" the complexities of job scheduling and control by relying on more exotic scheduling and control tools.

Effects of Contemporary Management Practices

This last section closes the discussion of scheduling by appropriately returning to the topic of management. In the 1970s, North American managers allowed batch and job production scheduling and control

TABLE 13.4 Manufacturing Scheduling Overview

Manufacturing Environment	General Nature of Scheduling
Project	Activity scheduling and controlling (as well as overall project planning) may rely on program evaluation and review technique or critical path method. Large project complexity, cost, and uncertainties involved justify these tools. Smaller projects and single tasks may be scheduled with Gantt charts.
Job or Batch	Scheduling is time consuming due to low- or intermediate-volume output coupled with irregular production of any given item. Production typically occurs on flexible resources in functional or process layouts where considerable variation in products, routings, low sizes, and cycle times — along with the competition among jobs (customers) for resource allocation — adds to the scheduling burden. Rescheduling may be common.
Continuous or Repetitive	Regular — if not constant — production and equipment dedicated to one or a few products (e.g., lines or cells) combine to decrease the scheduling problem. In process flow systems, scheduling is minimal except for planned maintenance, equipment or product changeovers, and so forth. In repetitive production, line balancing may be used to assign work; JIT's pull system, regularized schedules, and mixed-model scheduling can closely synchronize output with demand and can accommodate demand variation.

systems to become too complicated, cumbersome, and costly. A more competitive approach lies in the simplification of the production environments themselves [Schonberger and Knod, 1994; Steudel and Desruelle, 1992; Schneiderjans, 1993]. Though necessary to some degree, scheduling itself adds no value to outputs; as such, it ought to be a target for elimination where possible and for streamlining when it must remain. Application of contemporary management practices, such as the principles detailed in Table 13.3, has been shown to improve scheduling, largely by removing the *causes* of the problems, that is, the factors that created a need for complicated and costly scheduling systems.

Steudel and Desruelle [1992] summarize such improvements for scheduling and related production control activities, especially in group-technology environments. Regarding scheduling, they note that manufacturing cells largely eliminate the scheduling problem. Also, sequencing is resolved at the (decentralized) cell level, and mixed-model assembly and kanban more easily handle demand variations. In similar fashion, manufacturing process simplifications foster improvements throughout the production planning and control sequence.

Just-in-time (JIT) management, for example, has been shown to greatly reduce the burden of these activities, especially scheduling and control [Vollmann et al., 1992]. Attempts to describe a "JIT scheduling system", however, are unnecessary; it is more productive to devote the effort to eliminating the need for scheduling at all. At this writing, it remains an oversimplification to suggest that the mere pull of customer demand is sufficient to *fully* schedule the factory, but that is a worthy aim. In sum, the less attention managers are required to devote to scheduling, the better.

Defining Terms

Management: Activities that have the goal of ensuring an organization's competitiveness by creating, implementing, and improving capacity required to provide goods and services that customers want.

Process: A particular combination of resource elements and conditions that collectively cause a given outcome or set of results.

Scheduling: Activities through which managers allocate capacity for the immediate and near-term future.

References

Bateman, T. S. and Zeithaml, C. P. *Management: Function and Strategy, 2nd ed.*, Richard D. Irwin, Burr Ridge, IL, 1993.

Blackburn, J. D. *Time-Based Competition*, Business One-Irwin, Homewood, IL, 1991.

Camp, R. C. *Benchmarking.* ASQ Quality Press, Milwaukee, WI, 1989.

Evans, J. R. *Applied Production and Operations Management, 4th ed.*, West, St. Paul, MN, 1995.

Hall, R. *Zero Inventories,* Dow Jones–Irwin, Homewood, IL, 1983.
Hammer, M. and Champy, J. *Reengineering the Corporation,* HarperCollins, New York, 1993.
Imai, M. *Kaizen: The Key to Japan's Competitive Success,* Random House, New York, 1989.
Kerzner, H. *Project Management: A Systems Approach to Planning, Scheduling, and Controlling, 3rd ed.,* Van Nostrand Reinhold, New York, 1989.
Nakajima, S. *Introduction to TPM: Total Productive Maintenance,* Productivity Press, Cambridge, MA, 1988.
Schniederjans, M. J. *Topics in Just-In-Time Management,* Allyn & Bacon, Needham Heights, MA, 1993.
Schonberger, R. J. *Japanese Manufacturing Techniques: Nine Hidden Lessons in Simplicity,* Free Press, New York, 1982.
Schonberger, R. J. *Building a Chain of Customers,* Free Press, New York, 1990.
Schonberger, R. J. and Knod, E. M., Jr. *Operations Management: Continuous Improvement, 5th ed.,* Richard D. Irwin, Burr Ridge, IL, 1994.
Shingo, S. *A Revolution in Manufacturing: The SMED [Single-Minute Exchange of Die] System,* Productivity Press, Cambridge, MA, 1985.
Steudel, H. J. and Desruelle, P. *Manufacturing in the Nineties,* Van Nostrand Reinhold, New York, 1992.
Suzaki, K. *The New Manufacturing Challenge: Techniques for Continuous Improvement,* Free Press, New York, 1987.
Vollmann, T. E., Berry, W. L., and Whybark, D. C., *Manufacturing Planning and Control Systems, 3rd ed.,* Richard D. Irwin, Burr Ridge, IL, 1992.

Further Information

Periodicals
Industrial Engineering Solutions. Institute of Industrial Engineers.
Industrial Management. Society for Engineering and Management Systems, a society of the Institute of Industrial Engineers.
Journal of Operations Management. American Production and Inventory Control Society.
Production and Inventory Management Journal. American Production and Inventory Control Society.
Production and Operations Management. Production and Operations Management Society.
Quality Management Journal. American Society for Quality.

Books
Camp, R. C. *Business Process Benchmarking,* ASQC Quality Press, Milwaukee, WI, 1995.
Orlicky, *Materials Requirements Planning,* McGraw-Hill, New York, 1975.
Stonebraker, P. W. and Leong, G. K. *Operations Strategy.* Allyn & Bacon, Needham Heights, MA, 1994.

13.3 Capacity

Michael Pinedo and Sridhar Seshadri

The **capacity** of a system is defined as the maximum rate of production that can be sustained over a given period of time with a certain product mix. **Capacity management** focuses on the allocation and management of resources; it therefore affects almost every decision in a firm. It has an impact on lead times, inventories, quality, yield, and plant and maintenance costs.

Short-term capacity management contributes to meeting customer due dates, controlling inventories, and achieving high levels of labor and plant productivity. Medium-term capacity management deals with make or buy decisions, subcontracting, inventory levels, assignment of products to processes, and a variety of other decisions that affect production costs as well as customer service. Long-term capacity management deals with the planning of entire networks of facilities, determining facility locations, technology choices, and other economic factors. Long-term capacity expansion decisions have strategic implications for the firm and have to be taken under conditions of uncertainty in demand, technology, and competition.

Definition of Capacity and Measurement

In the first step of computing the capacity of a production facility, the appropriate groupings of machines that will form the basis for the analysis have to be determined. Each such grouping is called a **work center.** Dependent upon the purpose of the analysis, a work center may be an entire plant, a work area (such as turning or milling), or a single machine. The collection of all work centers, say M, will be referred to as the system. In the second step, the following data with regard to work center j, $j = 1,2,\ldots,M$, have to be compiled:

- The product mix, $(x_1, x_2, \ldots, x_N)$, where x_i is the fraction of all products in the product mix, that are of type i.
- The mix of products that will use work center j, $(y_{1j}, y_{2j}, y_{3j}, \ldots, y_{Nj})$, where y_{ij} is the fraction of product i that will be produced at work center j.
- The average lot size, L_i, in which product i will be produced at work center j.
- The setup time, S_i, for a lot and the run time, r_i, for each unit in the lot.

Let q_i denote the processing time per unit of product i and p_j the average processing time for a unit of the product mix at work center j. Based on the data,

$$q_i = S_i / L_i + r_i$$

and

$$p_j = \sum_{i=1}^{N} \left(q_i \; x_i \; y_{ij} \right).$$

The **rated** (also called theoretical, nominal, or standing) capacity of work center j, denoted by C_j, is defined as $C_j = 1/p_j$.

Consider the following example: the raw materials for a total of 100 units are released into the system, and the desired product mix is $(x_1, x_2, \ldots, x_N)$. Then work center j will need to process $100x_1y_{1j}$ units of type 1, $100x_2y_{2j}$ units of type 2, and so forth. Therefore, $100p_j$ is the time required to process all these units. The capacity is thus given by $1/p_j$. The capacity of the system, C_{system}, is defined as the smallest of all the C_js. The work center with the smallest capacity is called a bottleneck.

Typically, prior to these calculations, process analysis is used to determine the fractions y_{ij} (called the product routing decisions) and the lot sizes, L_i. The definition of C_j can easily be generalized to include multiple types of resources, such as machines, labor, space, material-handling equipment, and utilities. It is a matter of practical importance that the actual capacity need not be equal to C_j. With regard to work center j, let T_{av} denote the time period for which work is scheduled (such as two out of three shifts), T_{std} the standard hours of work produced, and T_{work} the hours actually worked. Based on these notions we can define the following concepts: (1) the utilization, $U_j = T_{\text{work}}/T_{\text{av}}$ (≤ 1) and (2) the efficiency, $E_j = T_{\text{std}}/T_{\text{work}}$.

The **capacity available** is said to equal $T_{\text{av}} \times C_j \times U_j \times E_j$. In this definition, the value of U_j reflects the fraction of time that work center j is unavailable due to breakdowns, repair, and preventive maintenance as well as the fraction of time it is not producing due to lack of work.

Factors that Affect Capacity

The major factors that affect capacity include

- Product mix
- Lot size
- Product yield, quality, rework, and rejection

- Routing and scheduling
- Input control and work regulation

The impact of the first three factors is clear from the formulas that define capacity. Product yield can be an important factor, especially in the microelectronics and process industries. If the product itself can be classified into several grades (such as the speed of a CPU chip), then quality too will play a major role in determining capacity. Rework reduces the capacity, especially when it is performed at the work center that was the cause of the rework. See also the section on the use of queueing networks for a further discussion on rework and yield. (The traditional method for dealing with rework and repair has been to include these times in the processing times themselves.)

Scheduling decisions are extremely important for ensuring twin goals: that resources are not idle for lack of work and that the buildup of work in progress inventory is kept minimal. While it clear that improper sequencing may lead to low levels of utilization, examples in practice as well as in theory show that excessive work in the system can actually lead to a reduction in throughput and thereby capacity. In recent years, it has also become more evident that proper timing of the release of work *into* the system can achieve the goals of minimizing inventory and maximizing capacity utilization.

Capacity Planning and Control Methods

The planning horizon chosen for capacity planning depends on the nature of the business. For example, capacity expansion plans could extend well over a decade for process industries but only 3 to 5 years for light engineering firms. The objective in capacity planning depends strongly on whether the planning is done for the short, medium, or long term.

Short-Term Capacity Planning

Short-term planning refers to the day-to-day management of work. It is well known that having the necessary resources for carrying out a plan in the aggregate (see the next section for an example of aggregate planning) is not sufficient to ensure that the plan can be executed in practice. Short-term planning can help bridge this gap between the aggregate plan and actual shop floor execution. With reference to the formula for capacity, an objective of short-term planning is to make the value of utilization (U) as close to unity as possible. The other objectives in short-term capacity planning include achieving the production target and meeting due dates, maintaining minimal inventory of work in progress (WIP), and controlling overtime. The short-term plan takes as the inputs higher-level decisions regarding the availability of resources, targets for finished goods and customer orders to be executed, along with due dates and priorities. The decisions that impact capacity in the short term include lot sizing, sequencing, controlling the release of work, routing of work, scheduling overtime, labor assignment, expediting, and ensuring that all the materials and resources required for carrying out the planned work are available at the right place and at the right time. These decisions are interrelated and complex. A recent innovation for short-term capacity management has been the introduction of manufacturing execution systems (MES). An advanced MES can provide support on a real-time basis for the scheduling, loading, and recording of work. These systems have become increasingly important, not just because of the complexity of the decision-making process but also because of the fact that traditional materials requirements planning (MRP) packages simply assumed unlimited capacity at all work centers. The MRP approach proved to be inadequate when firms were faced with shortening delivery lead times and growing product variety.

Medium-Term Capacity Planning

In the medium term, the objective of capacity planning is to minimize the cost of resources subject to meeting customer service levels. The decision variables normally include labor, overtime, the number of shifts in each period, the production volume in each period, the product mix, the average lot size, the level of subcontracting, the level of work in progress, and finished goods inventory. The inputs are the demand forecasts, the lead times for procuring materials, the lead times for production, resource requirement per unit of each product, and the service levels to be maintained over the planning horizon. The typical horizon can be as short as 2 weeks and as long as 1 year. Three different planning methods are discussed below: the mathematical programming approach, the capacity requirements planning method and the queueing network method.

Mathematical Programming

The medium-term capacity planning problem can be formulated either as a linear program or as a mixed integer program. The linear program ignores the integrality of labor and setups and cannot take into account explicitly a second or third shift option. In both formulations, it is convenient to group products into product families. The objective function may include wages, overtime costs, costs of hiring or laying off workers, setup costs, holding costs, and costs of subcontracting. The planning horizon is partitioned into periods (weeks or months). The constraints typically include

Inventory balance equations for each period:

opening inventory + production – sales = closing inventory

Resource requirement constraints for each period:

setup plus run time needed for production ≤ capacity of the resource
+ subcontract contract hours

Labor balance constraints for each period:

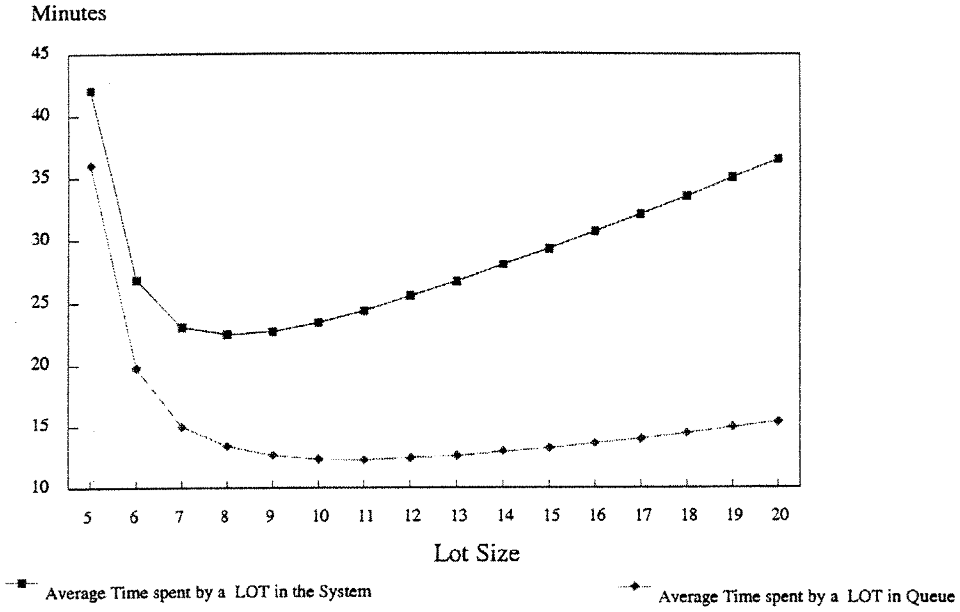
labor at the beginning of the period + number of workers hired
– number of workers fired = labor at the end of the period

Queueing Network Analysis

The 1980s saw the emergence of queueing theory as an approach for estimating and planning capacity. A production facility can be modeled as a network of queues, in which jobs of different types arrive randomly and, if accepted, enter the network and get processed in either a deterministic or random sequence (thereby catering to rework and product mix variations) and leave the system. It is in the modeling of the production facility as a queueing network that a planner can appreciate the impact of uncertainty and the close relationship between capacity and production lead times. For example, consider a simple single server queue whose utilization is U, in which arrivals come in according to a Poisson process, and job processing times are arbitrarily distributed. The average waiting time in this queue is proportional to the variability of the service time divided by $(1-U)$. The queueing approach allows the planner to establish the trade-offs between capacity and lead time, lot size and lead time, and sharing or not sharing of resources. The approach also allows the user to evaluate alternate routings, consider alternate configurations of the layout of resources, analyze the effect of overtime, experiment with different transfer lot sizes, and analyze the impact of breakdowns. As an example of this approach, the trade-off between lot size and the production lead time is shown in Fig. 13.1.

In this figure, the setup time per piece reduces as the lot size increases — thus leading to greater capacity. The greater capacity leads to smaller queueing delays for lots. However, the time spent in the system also includes the time spent waiting for a lot to build up at the work center, called the lot delay. The trade-off is due to these two effects and can be evaluated to choose an optimal lot size. Careful experimentation is often necessary to compute the jointly optimal lot sizes for several work centers. Similarly some experimentation is necessary when allocating labor to machines or processes because sharing a common resource can lead to interference (in the queueing literature referred to as the "machine interference problem").

A number of queueing network analysis software packages are available that employ rapid approximation techniques for evaluating the trade-offs discussed above. The queueing network approximation approach, however, *does not* allow the planner to capture the distribution of flow times through the



Arrival Rate of Jobs = 0.8/min., Run Time = 1.0 min., Setup Time = 1.0 min.

Arrival Process is Poisson, Service time is exponentially distributed, single machine (server)

FIGURE 13.1 Use of queueing theory for determining optimal lot size.

system, study the effect of priorities or expediting, or regulation of work into the system. Such finer details can be obtained only by constructing a simulation model of the system.

Capacity Requirements Planning

The manufacturing resources planning framework (MRPII) suggests four techniques for capacity planning, namely, **capacity planning using overall factors** (CPOF), **capacity bills, resource profiles, and capacity requirements planning** (CRP). The choice of the technique depends on the industry and application.

CPOF uses data with regard to the direct labor hours required to make a product, the historical percentage of total hours used in each work center, and the production plan for each period. Using the production plan, the total hours required for the system are first calculated and then allocated to the work centers using the historical percentages. This method is appropriate when demand and product mix are steady and production lead-times are short.

Example

Products A and B have the processing requirements given in Table 13.5. There are two work centers, DEPT1 and DEPT2. Historically, 70% of the work load has gone to DEPT1 and the balance to DEPT2. This breakup of work load is based on the (given) historical product mix of 1:1. We are given the production plan for the two products, as shown Table 13.6. The capacity requirements using CPOF are also shown in Table 13.6.

The capacity bills (or labor bills) technique uses the same information as CPOF, but does not allocate the total hours to the work centers. Instead, the load for each work center due to each product is computed separately. This method is appropriate when demand is steady, product mix varies from period to period, and the production lead times are short. Capacity requirements computed using capacity bills for the same example are shown in Table 13.6.

The Resource Profiles technique uses the **operation set back chart** as additional input data. The operation set back chart is a Gantt chart that maps the capacity requirement for a product in two

TABLE 13.5 Processing Requirements

Part	Department	Operation (in sequence)	Lot Size	Run Time (min)	Setup Time (min)	Time per Part (min)	Planning Lead-time (pd)
A	2	1.00	20.00	0.05	1.00	0.10	1.00
	1	2.00	20.00	0.10	1.00	0.15	1.00
B	1	1.00	40.00	0.20	1.00	0.23	1.00
	2	2.00	40.00	0.05	0.50	0.06	1.00

TABLE 13.6 Production Plan and Capacity Requirements

		Period			
	(Backlog)	1	2	3	4
Production plan for A		20.00	30.00	25.00	15.00
Production plan for B		10.00	40.00	10.00	30.00
CPOF Calculations					
Total hours needed for A		5.00	7.50	6.25	3.75
Total hours needed for B		2.88	11.50	2.88	8.63
Total		7.88	19.00	9.13	12.38
Department 1 (70%)		5.51	13.30	6.39	8.66
Department 2 (30%)		2.36	5.70	2.74	3.71
Capacity Bill Calculations					
Department 1, product A		3.00	4.50	3.75	2.25
Department 1, product B		2.25	9.00	2.25	6.75
Total Department 1		5.25	13.50	6.00	9.00
Department 2, product A		2.00	3.00	2.50	1.50
Department 2, product B		0.63	2.50	0.63	1.88
Total Department 2		2.63	5.50	3.13	3.38
Resource Profile Calculations					
Department 1, product A		3.00	4.50	3.75	2.25
Department 1, product B	2.25	9.00	2.25	6.75	0.00
Total Department 1	2.25	12.00	6.75	10.50	2.25
Department 2, product A	2.00	3.00	2.50	1.50	0.00
Department 2, product B		0.63	2.50	0.63	1.88
Total Department 2	2.00	3.63	5.00	2.13	1.88

dimensions — work center on the y-axis vs. time on the x-axis. The production plan can then be converted to show the period in which the capacity will be required. This method is appropriate when demand and/or product mix variations are coupled with relatively long production lead times. For the previous example, if it is given that each operation takes one period to perform (called the planning lead time), then the capacity requirements will look as shown in Table 13.6.

The CRP technique is similar to the resource profiles technique, except that it uses the MRP data, accounts for work in progress, and additionally plans for service parts. This technique is more suitable for short-term planning purposes. The finite loading techniques embodied in MES will eventually replace the CRP method.

Planning for the Long Term

The objective of capacity planning in the long term is essentially strategic. The key decision variables include the location, size and technology of facilities, and the timing of the investment decisions for capacity expansion as well as equipment replacement. Other important decisions that bear upon capacity planning for the long term include partnerships for technology development, distribution system design, and the choice of the supply base and suppliers. Given the enormous scope and the uncertainties involved in long-term capacity planning, we shall only describe three approaches that have been used to model this problem. The approaches are dynamic programming, stochastic programming, and game theoretic models set in the industrial organization economics framework. Recent developments in the area of supply chain design are not covered in this list. Factors and techniques that are important for long-term capacity planning decisions (and that have not been covered) include tax incentives, government regulation, international laws, and investment analysis of projects under uncertainties.

The Dynamic Programming Approach

In this approach, demand is given either as a deterministic or as a random function of time, and plant costs are given as a function of size and time. Technological uncertainties can be built into the models, and a discount factor can be used to evaluate different expansion strategies. The decisions are when to invest and in what magnitude. The basic trade-off is between reduction in per unit cost of capacity (due to economies of scale) and having excess capacity. Closed-form solutions for the capacity expansion problem are available for simple demand and cost functions. The approach becomes computationally intensive with an increasing number of time periods, with a larger number of products as well as locations, and with the modeling of uncertainties in the technology.

Stochastic Programming

In this approach, the modeler evaluates expansion strategies under multiple scenarios. Consider, for example, a two-period, single resource capacity planning problem. The capacity required in the first period is 100. The capacity requirements in the second period can either be 100 in the low (*L*) demand scenario with probability p_L or 200 in the high (H) demand scenario with probability p_H. The demand in the second period will be known at the end of the first period. There are two technologies. Technology 1 (2) can be installed in capacity multiples of 100 (200) and each unit of 100 (200) costs \$1000 (\$1500). Let X_{i1}, $i = 1,2$ be the integer units of technology *i* installed in the first period, and X_{i2j}, $i = 1,2$; $j = L, H$, be the integer units of technology *i* installed under scenario *j* in the second period. The objective is to minimize the total expected cost in the two periods, and we are given that all demand has to be met. Then the optimization problem can be written as shown below.

$$\text{Min } 1000\,X_{11} + 1500\,X_{21} + p_L 1000\,X_{12L} + p_H 1000\,X_{12H} + p_L 1500\,X_{22L} + p_H 1500\,X_{22H}$$

subject to

$$\begin{array}{lll}
\text{First period demand:} & 100\,X_{11} + 200\,X_{21} & \geqq 100 \\
\text{Second period low } (L) \text{ demand:} & 100\,X_{11} + 200\,X_{21} + 100\,X_{12\mathrm{L}} + 200\,X_{22\mathrm{L}} & \geqq 100 \\
\text{Second period high } (H) \text{ demand:} & 100\,X_{11} + 200\,X_{21} + 100\,X_{12\mathrm{H}} + 200\,X_{22\mathrm{H}} & \geqq 200
\end{array}$$

The optimal solution is to invest in one unit of the technology 1 in the first period if $p_L \leq 0.5$ and in one unit of technology 2 otherwise. There are a number of advantages in using this approach: the entire arsenal of mathematical programming is available for modeling the constraints as well as the dynamics and for choosing the objective function(s). The reaction of the competition can be taken into account in the model as well as taxes, subsidies, and regulation. This approach for capacity planning has been used in several industries, such as the electric utilities, oil exploration, the PVC industry, and several other process industries.

Game Theoretic Approach

Long-term capacity planning would need to include many additional factors such as preemptive behavior, competitive reaction to capacity changes, and the impact on market share. Game theoretical models can be used to understand these issues better. An introduction to the subject can be found in Lieberman [1987] and to the modeling ideas in Tirole [1990].

In closing this section on long-term capacity planning, it is important to mention the capacity strategy underlying just-in-time (JIT) implementations. In the JIT philosophy [Shingo, 1989], wasted labor time is considered one of the seven cardinal wastes — it is preferred that machines, instead of people, wait. While this strategy underscores excess capacity, it also goes hand in hand with the rest of the JIT strategy, such as building in-house expertise in the design and production of machines. More information about manufacturing strategy can be obtained from Hill [1993].

Defining Terms

Calculated capacity of a work center: Equals the rated capacity multiplied by the utilization, the efficiency, and the activation of that work center.

Capacity: The maximum rate of production that can be sustained over a given period of time with a certain product mix.

Capacity management: Allocation and management of resources.

Capacity planning using overall factors (CPOF), **capacity bills, resource profiles,** and **capacity requirements planning** (CRP): Four medium-term capacity planning techniques suggested in the manufacturing resource planning framework.

Operation set back chart: A Gantt chart that maps the capacity requirement for a product with the work center on the y-axis and time on the x-axis.

Rated (also called theoretical, nominal, or standing) Capacity of a work center: The inverse of the average processing time of a unit of work at that work center.

Work centers: The appropriate groupings of machines that form the basis for the analysis of capacity.

References

Bitran, G. R. and Morabito, R. Open queueing networks: performance evaluation models for discrete manufacturing systems, *Prod. Operat. Mgt.*, 5(2): 163–193, 1996.

Blackstone, J. H., Jr. *Capacity Management*, South-Western, Cincinnati, OH, 1989.

Buzacott, J. A. and Shanthikumar, J. G. *Stochastic Models of Manufacturing Systems*, Prentice Hall, Englewood Cliffs, NJ, 1993.

Hax, A. C. and Candea, D. *Production and Inventory Management*, Prentice Hall, Englewood Cliffs, NJ, 1984.

Hill, T. *Manufacturing Strategy: Text and Cases, 2nd ed.*, Richard D. Irwin, Burr Ridge, IL, 1993.

Li, S. and Tirupati, D. Dynamic capacity expansion problem with multiple products: technology selection and timing of capacity additions, *Operat. Res.*, 42(5): 958–976, 1994.

Lieberman, M. B. Strategies for capacity expansion, *Sloan Mgt. Rev.*, Summer: 19–27, 1987.

Luss, H. Operations research and capacity expansion problems: a survey, *Operat. Res.*, 30(5): 907–945, 1982.

Malcolm, S. A. and Zenios, S. A. Robust optimization for power systems capacity expansion under uncertainty, *J. Operat. Res. Soc.*, 45(9): 1040–1049, 1994.

Ross, S. M. *A Course in Simulation*, Macmillan, New York, 1990.

Shingo, S. *A Study of the Toyota Production System*, Productivity Press, Cambridge, MA, 1989.

Tirole, J. *The Theory of Industrial Organization*, MIT Press, Cambridge, MA, 1990.

Further Information

For further details on capacity requirements planning and for other definitions of capacity see Blackstone [1989]. Details on mathematical programming applications for capacity planning can be found in Hax and Candea [1984]. For a comprehensive introduction to models employing the queueing network approach for capacity planning and control see Buzacott and Shanthikumar [1993]. An introduction to simulation modeling is given in Ross [1990]. The reader is referred to the survey article [Luss, 1982] for details on the use of dynamic programming for solving capacity expansion problems. For a mathematical programming approach for solving technology selection and capacity expansion problems, the reader is referred to Li and Tirupati [1994]. References and other details regarding stochastic programming applications for capacity expansion can be found in Malcolm and Zenios [1994].

13.4 Inventory

Steven Nahmias

Inventories are of concern at many levels of our economy. To be competitive retailers must maintain stocks of items demanded by consumers. Manufacturers require inventories of raw materials and work in process to keep production lines running. Inventories of spare parts must be available in repair centers for equipment maintenance and support. On a macro level, inventories are used to measure the health of the economy: larger inventories usually mean a slowdown of economic activity.

Why is inventory management so vital? Because the investment in inventories in the United States is enormous. As of April 1997, total business inventories in the United States was $1.02 *trillion* comprised of 44% manufacturing, 31% retail, and 25% wholesale. (Source: U.S. Department of Commerce Data.) Efficient management of inventories is clearly a top priority in our competitive economy. Inventory management is one of the most successful areas of application of operations research. For example, major weapons systems in the military, worth hundreds of billions of dollars, have been successfully managed using sophisticated mathematical **models** [Muckstadt, 1974]. Retailers employ large-scale information storage and retrieval systems with electronic data interchange to keep close tabs on inventory levels and consumer buying patterns.

This section is a brief overview of the models and methods for managing inventories when the following characteristics are present. There is a demand or need for the inventory, which may or may not be known in advance. There is an opportunity to replenish the inventory on an ongoing basis. Finally, there are accounting costs associated with various aspects of the inventory management process that can be measured or estimated.

Fundamentals

Let's start by reviewing the cornerstones of inventory modeling (here, the term model means a mathematical representation of a physical system). In the context of inventory control, the purpose of a model is to answer two questions: when should an order be placed (or production initiated) and how large should it be. Different control rules are appropriate in different circumstances, depending on several factors. These factors include the type of inventory, the motivation for holding the inventory, and the physical characteristics of the system.

Inventories can be classified in many different ways. One is based on increasing order of value added. This classification, appropriate in manufacturing contexts, gives the following categorization (listed in order of value added):

1. Raw materials
2. Components
3. Work in process
4. Finished goods

Other classification systems might be appropriate in other contexts. In order to understand inventory management, we must understand the underlying economic justification for holding inventories. Some of these are

1. *Economies of scale.* When substantial fixed costs accompany a replenishment, it is economical to produce in large lots. As we later see, the trade-off between fixed costs and **holding costs** forms the basis for the **EOQ** (economic order quantity) model, which itself is the basis for virtually all inventory modeling.

2. *Uncertainties.* Several uncertainties result in incentives to maintain inventories. The most important is uncertainty of the demand. In most contexts, demand cannot be predicted exactly, and inventories provide a buffer against demand uncertainty. Other relevant uncertainties include uncertainty of supply, uncertainty in replenishment **lead times**, uncertainties in costs, and uncertainties in the future value of the inventory.
3. *Speculation.* Holding inventory in anticipation of a rise in its value or a scarcity of supply is an example of the speculative motive. For example, silver is a requirement for production of photographic film. Major producers, such as Kodak, were at a competitive disadvantage when silver prices rose rapidly in the late 1970s.
4. *Transportation.* With the advent of the global economy, firms are producing and marketing products worldwide. One result is substantial in-transit or pipeline inventories. To reduce pipeline inventories, some companies choose to locate manufacturing facilities domestically even though labor costs may be higher in the U.S. than overseas.
5. *Smoothing.* Due to production capacity constraints, it makes sense to build inventories in anticipation of a sharp rise in demand. Many retailers do most of their business during the holiday season, for example. As a result, orders to manufacturers increase dramatically prior to year's end. Manufacturers must be prepared for this surge in demand.

Characteristics of Inventory Systems

The assumptions one makes about the underlying characteristics of the system determine the complexity of the resulting model. These characteristics include

- Demand
- Costs
- Review intervals
- Lead times
- Treatment of excess demand
- Changes over time
- Multiple echelons
- Item interactions

I will briefly review the most common cases treated.

Demand

The simplest case is when demand is known and constant. In other words, when it can be predicted exactly and the number of units consumed is the same every period. Known constant demand is rarely the case, but it can be a reasonable approximation. There are many ways to relax this assumption, but two are the most important. One is to assume that demand is known, but changing over time. This is known as nonstationary demand and is appropriate if there are significant seasonal variations, trends, or growth. The second is to allow for uncertainty of demand. In this case, demand is assumed to be random (or stochastic). Stochastic inventory models are based on an underlying probability distribution from which demand realizations are drawn. This distribution might be estimated from a past history of observations or from expert opinion. In most real-life environments, both nonstationarity and uncertainty are probably present to some extent. Little is known about dealing with these simultaneous sources or variation, however.

Costs

How costs are assessed also plays a major role in determining the complexity of the resulting model. Costs may be classified into the following broad categories: order costs, holding costs, and penalty costs. These categories incorporate most of the costs one encounters in practice. Let us consider each in turn.

Order costs are all costs that depend upon the quantity ordered or produced. The most common assumption is that there are both fixed and variable components. That is, the cost of ordering Q units, e.g., $C(Q)$, is

$$C(Q) = 0 \text{ if } Q = 0$$

$$C(Q) = K + cQ \text{ if } Q > 0$$

Here K is the fixed cost or setup cost and c is the marginal cost of each unit. More complex order-cost functions result when, for example, the supplier offers quantity discounts. Simpler models ignore fixed costs.

Holding costs, also known as carrying costs, are all costs that accrue as a result of holding inventory. Holding costs are composed of several components. These include the costs of:

1. Providing the physical space to store the item
2. Taxes and insurance
3. Breakage, spoilage, deterioration, pilferage, and obsolescence
4. Opportunity cost of alternative investment

In most cases, the last item is the most significant component of the holding cost. Money tied up in inventories could otherwise be invested elsewhere in the firm. This return could be quite substantial and relates to financial measures such as the cost of capital, the hurdle rate for new projects, and the internal rate of return. When inventory levels change continuously, holding costs can be difficult to calculate, since they are also changing continuously.

Penalty costs result from having insufficient stock to meet a demand when it occurs. Penalty costs include bookkeeping expenses when excess demand is backordered, foregone profit when excess demands are lost, and possible loss of customer goodwill. The last component is extremely important and difficult to measure. For example, loss of goodwill could affect the future demand stream of the product.

Review Intervals

The review interval corresponds to the times inventory levels are checked and reorder decisions made. Periodic review means that the opportunity to place orders occurs only at discrete points in time. Today, many systems are continuous review, which means that transactions are reported as they occur. This is the case, for example, with bar-code scanners that transmit information from point of sale to a centralized computer. Mathematical inventory models have been developed for both cases.

Lead Times

The lead time is the time that elapses from the point that an order is placed (or production is initiated) until the order arrives (or production is completed). The simplest assumption is that the lead time is zero. This may sound unrealistic, but is appropriate in some circumstances. When review periods are long and the replenishment lead time is less than a review period, assuming zero lead time is reasonable. In most environments, however, the lead time is substantial and must be included in the formulation of the model. In these cases, lead times are almost always assumed to be fixed and known. However, in many cases there is substantial uncertainty in the lead time. Mathematically, random lead times present many difficulties, so practical real-world applications rarely allow for them.

Treatment of Excess Demand

As noted earlier, excess demand may result in either backorders or lost sales. Another possibility is partial backordering, where some demands are backordered and some are lost. When excess demands are backordered, costs can be charged in several ways. The most common is a one-time cost for each unit of unfilled demand. In some circumstances, it is more appropriate to use a time-weighted backorder cost. This might be the case when the item is required in another process.

Changes over Time

Some inventories change over time. An example is perishable items with a known expiration date. Examples of perishables include processed foods, photographic film, and human blood. In these cases, the utility of an item is essentially constant until it expires, at which time the utility drops to zero. A somewhat different situation occurs when a fixed proportion of the inventory is lost each period due to spoilage, evaporation, or radioactive decay. This is known as exponential decay and may be a reasonable approximation of the more complex fixed-life perishable case. With the growth of the high-tech sector of the economy, obsolescence has become a more significant problem. In this case the inventory is not changing, but the environment is. The net result, that the items are no longer useful, is the same, however.

Multiple Echelons

In a large integrated inventory-control system, it is common for items to be stored at multiple locations. Retailers store inventory at regional distribution centers (DCs) before shipping to retail outlets. There may be several levels of intermediate storage locations between the producer and the consumer. Military applications sparked the original interest in these so-called **multiechelon** systems. The investment in spare parts in the military is huge, possibly as high as $1 trillion worldwide. The materiel support system includes as many as three levels or more. With the recent advent of EDI (electronic data interchange), interest in managing serial supply systems is greater than ever. These systems are known as "supply chains". The identification of unusual phenomenon such as the bullwhip effect (which corresponds to the increasing variance of orders as one moves from demand points to intermediate echelons to producing facilities), has contributed to the recent interest among academics and practitioners in supply chain management.

Item Interactions

Virtually all real-world inventory systems require simultaneous management of multiple items. It is not untypical to have hundreds of thousands of SKU's (stock keeping units) in one system. Often, interactions among the items arise that cannot be ignored. For example, if items compete for space or budget, explicit constraints expressing these limitations must be included into the analysis. In retailing, economic substitutes and complements are common. Hot dogs and hot dog buns are an example of complements, while hamburgers vs. hot dogs is an example of substitutes. Item interactions (such as these) are difficult to model.

The EOQ Model

The EOQ is the simplest mathematical inventory control model, yet is remarkably robust. The square root law that results appears frequently in more complex settings. The assumptions under which the EOQ model is exact are

- Demand is known and constant. The demand rate is λ units per unit time.
- Costs are assessed only against holding, at $\$h$ per unit held per unit time, and ordering at $K + cy$ per positive order of y units placed.
- The object is to find a policy that minimizes average costs per unit time.

As noted above, the objective of the analysis is to answer the questions (1) when should an order be placed? and (2) for how much? It turns out that the optimal policy is independent of the marginal ordering cost, c. Why is this so? Over an infinite horizon, all feasible policies must order exactly the demand. This will be paid for at the rate λc independent of the replenishment policy.

Assume for the time being that the order lead time is zero. In that case, one replenishes stock only when the level of on-hand inventory is zero. Any other strategy would clearly result in a higher holding cost. At the instant on-hand inventory hits zero, one places (and receives) an order. Suppose this order

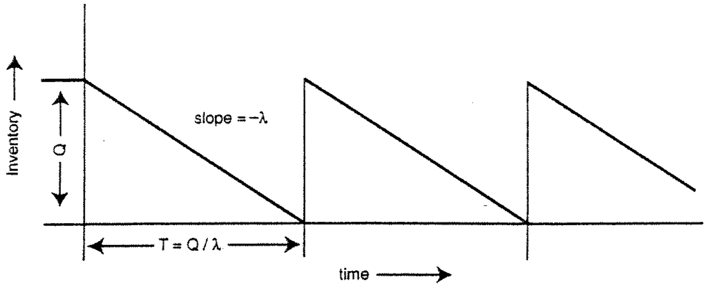


FIGURE 13.2 Inventory levels for EOQ model.

is for 5 units. This results in a sawtooth profile for the on-hand inventory as pictured in Fig. 13.2. Notice from Fig. 13.2 that the time between arrival of successive orders is Q/λ. Furthermore, the average on-hand inventory level is $Q/2$. From these observations alone, one can derive the EOQ formula.

The setup cost is incurred once each cycle. From Fig. 13.2 it is clear that the length of a cycle increases as Q increases, so that the average setup cost per unit time should be a decreasing function of Q. The average setup cost per unit time is K divided by the cycle length, Q/λ, giving $K\lambda/Q$.

The average holding cost per unit time is the average inventory level times the holding cost rate, which gives $hQ/2$. The optimal solution is found by differentiating $K\lambda/Q + hQ/2$ with respect to Q and set the resulting expression to zero to find the minimizing value of Q.

The result is the simple EOQ formula given by

$$Q=\sqrt{\frac{2K\lambda}{h}}.$$

This formula was discovered in 1915 by Ford Harris, an engineer with the Westinghouse Corporation. Amazingly, after more than 80 years and many thousands of technical papers on inventory theory, this formula remains the standard in many commercial inventory control systems. It is surprisingly robust. An error in the lot size or in the estimation of cost parameters results in significantly smaller penalties in the annual cost. For example, if one is using a lot size 50% larger than the optimal, the annual cost is only 8.33% higher than the optimal.

There are several relatively straightforward extensions to the basic model. These include (but are not limited to) (1) a positive order lead time, (2) a finite production rate, (3) quantity discounts, (4) constraints, and (5) backordering.

In this writer's opinion, the two most important generalizations of the basic EOQ model are to nonstationary demand and to random demand. A brief overview of the main results in each case follows.

Nonstationarity

Nonstationarity means that demands are changing over time. The easiest way to cast a non-stationary problem is as periodic review. That means that inventory levels are reviewed only at the beginning of discrete points in time, called periods. All demand is assumed to occur at one point within a period, and costs are assessed at one point in the period.

Suppose that demands over the next n periods are known constants. As with the EOQ model, assume that costs are charged against holding and setup only. The form of the optimal order policy is fundamentally different from the EOQ. Finding an optimal policy efficiently depends on the following result:

> The optimal policy is an exact requirements policy, that is, in any period in which an order is placed, the size of that order is exactly the sum of the next k periods of demand where $1 \le k \le$ number of periods remaining in the horizon.

This result means that an optimal policy is completely specified by the periods in which ordering occurs. Forward or backward dynamic programming can be used to find optimal policies for even long planning horizons very efficiently. Nonstationary demand arises in several contexts. There are many situations where demands are relatively predictable (so randomness is not an issue), but there are anticipated peaks and valleys in the upcoming demand pattern. This would be the case, for example, for a highly seasonal retail item. Significant nonstationarities in demand also are common in MRP (materials requirements planning) systems. Even when end item demands are relatively smooth, the demand patterns for lower-level assemblies and components can be quite lumpy.

Randomness 1: The Newsvendor Model

Another fundamental extension of the EOQ model is to the case of demand uncertainty. Uncertainty in demand requires a fundamentally different way of looking at the system. Virtually all stochastic inventory models find policies to minimize expected costs. The use of the expected value as the appropriate operator can be justified by the law of large numbers. The law of large numbers says (roughly) that the arithmetic average of many draws from a fixed population eventually grows close to the expected value of the population. In the inventory context, that would suggest that the expected value is appropriate when the replenishment process is ongoing. By choosing a policy to minimize expected costs, one is guaranteed to minimize realized average costs over many planning periods. For one-shot replenishment decisions, the appropriateness of the expected value criterion is certainly not as clear.

As the EOQ model is the basis for all deterministic inventory models, so is the news vendor (originally "newsboy") model the basis for all stochastic inventory models. The situation is exactly that experienced by a news vendor. The product perishes quickly; that is, it can be used to satisfy demand for a single period only. A purchase decision must be made at the beginning of a planning period, and the demand during the period is a draw from a known probability distribution. Assuming a known probability distribution of demand is reasonable if there is a past history of demand observations during which the demand pattern has been stable. From this history, one can estimate both the shape and the parameters of the demand distribution.

There are several ways one might develop a cost structure for this system, but the easiest and most intuitive is the following. There are two ways one can err: by ordering too much or ordering too little. Ordering too much means that one pays for items that don't sell. Ordering too little means that excess demands are unmet, and profits foregone. Let us suppose that the cost of every unit purchased and not sold is c_o (for overage cost) and the cost of every unit of excess demand not filled is c_u (for underage cost). Furthermore, assume that the cumulative distribution function (cdf) of demand in a period is $F(t)$.

The solution to the news vendor problem turns out to be surprisingly simple. The order quantity, Q, which minimizes the expected costs of overage and underage for the period solves

$$F(Q) = \frac{c_u}{c_u + c_o}.$$

The right-hand side of this equation is known as the critical ratio. Note that, as long as both underage and overage costs are positive, the critical ratio must be between zero and one. How difficult this equation is to solve depends on the complexity of the demand distribution. However, since the cdf is a nondecreasing function, we know that this equation will always have a solution (as long as the distribution is continuous). Popular spreadsheet programs, such as Excel, include the inverses of the most common distributions, making this equation easy to solve in those cases. Under normally distributed demand (which is a very common assumption in practice), the optimal solution has the form

$$Q = \sigma z + \mu,$$

where μ and σ are, respectively, the population mean and standard deviation and z is the unit normal value corresponding to a left tail equal to the critical ratio.

Although the news vendor model is single period only, the form of the solution is exactly the same when stock can be carried from one period to the next and there are infinitely many periods remaining in the planning horizon. The only difference is that the overage and underage costs must be interpreted differently. As long as there is no fixed order cost, lead times can be incorporated into the analysis in a relatively straightforward manner as well. If the lead time is L periods, then the order up to level is found by inverting the $L + 1$-fold convolution of the single period demand distribution. When a salvage value is included equal to the purchase cost, the finite horizon solution can be found by solving a series of news vendor problems.

Randomness 2: The Lot Size Reorder Point Model

The periodic review multiperiod news vendor model is much more complex if one includes a fixed order cost. Since fixed costs are common in practice, a continuous review heuristic (i.e., approximate) model is much more popular. Continuous review means that the inventory level is known at all times. As long as demands do not occur in bulk, one has the opportunity to place an order when the inventory level hits a specified reorder level, say R.

Suppose there is a positive order lead time and the demand during the lead time is a random variable, D, with cumulative distribution function $F(t)$. As earlier, let λ be the expected demand rate. The following cost structure is assumed: ordering at $K + cQ$ per positive order of size Q, p per unit of backlogged demand, and h per unit held per unit time. The policy is when the inventory level hits R an order of size Q is placed. A heuristic analysis of this system leads to the optimal values of Q and R simultaneously solving the following two equations:

$$Q = \sqrt{\frac{2\lambda\left[\left(K + pn\left(R\right)\right]\right.}{h}}$$

$$1 - F\left(R\right) = \frac{Qh}{p\lambda}.$$

The term $n(R)$ is known as the loss integral. For normal demands, this function is tabled, but in general this term can be cumbersome to compute. Several researchers have recommended approximations that give good results and avoid the calculation of the loss integral. The simplest is to approximate Q by the EOQ, which gives fairly good results in most cases. If Q is given, finding R is equivalent to solving a news vendor problem.

Because it is often difficult to estimate the backorder cost, many users prefer to specify service levels instead. The service level can be defined in several ways, but the most common is the percentage of demands that can be met from stock. This is also known as the fill rate. Solving (Q,R) systems subject to a constraint on fill rate yields equations similar to those above. The reorder level is somewhat more difficult to find, however, even if one uses a simple approximation for 5. When a constraint on fill rate is specified, the reorder level R solves

$$n\left(R\right) = \left(1 - \beta\right)Q$$

where β is the fill rate. This equation requires inverting the loss function $n(R)$. The normal distribution is commonly assumed, and tables are used to perform the inversion. A recent application of (Q,R) models to a large-scale inventory system containing in excess of 30,000 parts is described in Hopp et al. [1997].

Historical Notes and Further Reading

As a subfield of operations research, inventory has long history. The EOQ model [Harris, 1915] predates most formal OR activities by almost 30 years. The origin of the news vendor model is unclear, but it appears to date to the late 1940s. Several important papers appeared in the early 1950s, which spawned the interest in this area among academics. These included the studies of Arrow et al. [1951] and Dvoretzsky et al. [1952a, 1952b]. The book by Whitin [1957] was important in linking inventory control to classical economics and was probably the origin of the (Q,R) model discussed here. Arrow et al. [1958] compiled a collection of highly technical papers, which served as the cornerstone of the mathematical theory of inventories. The results on the deterministic nonstationary problem are due to Wagner and Whitin [1958].

For those interested in further reading, both review articles and books provide good overviews of existing work. More comprehensive general reviews on inventory models can be found in Veinott [1966] and Nahmias [1978]. Several excellent and comprehensive review articles are contained in the book Graves et al. [1993]. There are also several reviews of particular subfields that might be of interest. These include a review of perishable inventory models [Nahmias, 1982], repairable inventory models [Nahmias, 1981], and inventory models for retailing [Nahmias and Smith, 1993]. Although out of print, Hadley and Whitin [1963] still provides an excellent summary of the basic models and theory. Other recommended texts include Brown [1967], Silver and Peterson [1975] (scheduled for a new edition soon), and Nahmias [1997]. Many technical journals include papers on inventory theory and practice. The following professional journals regularly carry articles on inventory theory: *Operations Research, Management Science, Industrial Engineering,* and *Naval Research Logistics,* to name a few.

Defining Terms

Model: A mathematical representation of a physical system.

Lead time: The elapsed time from the point an order is placed (or production is initiated) until the order arrives (or production is completed).

Multiechelon: An inventory system in which there are intermediate storage locations between producer and consumer.

Holding costs: Costs that result from physically carrying inventory. The main component is the opportunity cost of alternative investment.

EOQ: Economic order quantity given by the well-known square root formula.

References

Arrow, K. A., Harris, T. E., and Marschak, J. Optimal inventory policy, *Econometrica,* 19: 250–272, 1951.

Arrow, K. A., Karlin, S. A., and Scarf, H. E. *Studies in the Mathematical Theory of Inventory and Production,* Stanford University Press, Stanford, CA, 1958.

Dvoretzky, A., Kiefer, J., and Wolfowitz, J. The inventory problem I: case of known distributions of demand, *Econometrica,* 20: 187–222, 1952a.

Dvoretzky, A., Kiefer, J., and Wolfowitz, J. The inventory problem II: case of unknown distributions of demand, *Econometrica,* 20: 450–466, 1952b.

Harris, F. W. *Operations and Cost,* Factory Management Series, Shaw, Chicago, 1915.

Hopp, W. J., Spearman, M. L., and Zhang, R. Q. Easily implementable inventory control policies, *Operat. Res.,* 45: 327–340, 1997.

Muckstadt, J. A. A model for a multi-item, multi-echelon, multi-indenture inventory system, *Mgt. Sci.,* 20: 472–481, 1974.

Wagner, H. M. and Whitin, T. M. Dynamic version of the economic lot size formula. *Mgt. Sci.,* 5: 89–96, 1958.

Whitin, T. M. *The Theory of Inventory Management, rev. ed.,* Princeton University Press, Princeton, NJ, 1957.

Further Information

Brown, R. G. *Decision Rules for Inventory Management,* Dryden, Hinsdale, IL, 1967.

Graves, S. C., Rinnooy Kan, A. H. G., and Zipkin, P. H., Eds. *Handbooks in Operations Research and Management Science, Vol. 4,* Elsevier Science, Amsterdam, 1993.

Hadley, G. and Whitin, T. M. *Analysis of Inventory Systems,* Prentice Hall, Englewood Cliffs, NJ, 1963.

Nahmias, S. Inventory models, In *The Encyclopedia of Computer Science and Technology, Vol. 9,* Belzer, Holzman, and Kent, Eds., pp. 447–483, Marcel Dekker, New York, 1978.

Nahmias, S. Managing reparable item inventory systems: a review, In *Multilevel Production/Inventory Control Systems: Theory and Practice, Vol. 16,* L. Schwarz, Ed., TIMS Studies in the Management Sciences, pp. 253–277, North Holland, 1981.

Nahmias, S. Perishable inventory theory: a review, *Operat. Res.,* 30: 680–708, 1982.

Nahmias, S. and Smith, S. A. Mathematical models of retailer inventory systems: a review, In *Perspectives on Operations Management, Essays in Honor of Elwood S. Buffa,* Sarin, R., Ed., pp. 249–278, Kluwer Academic, Boston, 1993.

Nahmias, S. *Production and Operations Analysis, 3rd ed.,* Richard D. Irwin, Burr Ridge, IL, 1997.

Silver, E. A. and Peterson, R. *Decision Systems for Inventory Management and Production Planning, 2nd ed.,* John Wiley & Sons, New York, 1985.

Veinott, A. F. The status of mathematical inventory theory, *Mgt. Sci.,* 12: 745–777, 1966.

13.5 Quality

Matthew P. Stephens and Joseph F. Kmec

Although no universally accepted definition of **quality** exists, in its broadest sense quality has been described as "conformance to requirements", "freedom from deficiencies", or "the degree of excellence that a thing possesses". Taken within the context of the manufacturing enterprise, quality — or, more specifically, manufacturing quality — shall be defined as "conformance to requirements". This section focuses on the evaluation of product quality, with particular emphasis directed at statistical methods used in the measurement, control, and tolerances needed to achieve the desired quality. Factors that define product quality are ultimately determined by the customer and include such traits as reliability, affordability or cost, availability, user friendliness, and ease of repair and disposal. To ensure that quality goals are met, manufacturing firms have initiated a variety of measures that go beyond traditional product inspection and record keeping, which, by and large, were the mainstays of quality control departments for decades. One such initiative is total quality management (TQM) [Saylor, 1992], which focuses on the customer, both inside and outside the firm. It consists of a disciplined approach using quantitative methods to continuously improve all functions within an organization. Another initiative is registration under the ISO 9000 series [Lamprecht, 1993], which provides a basis for U.S. manufacturing firms to qualify their finished products and processes to specified requirements. More recently, the U.S. government has formally recognized outstanding firms through the coveted Malcolm Baldridge Award [ASQC, 1994] for top quality among U.S. manufacturing companies. One of the stipulations of the award is that recipient companies share information on successful quality strategies with their manufacturing counterparts.

Measurements

The inherent nature of the manufacturing process is variation. Variation is present due to any one or a combination of factors including materials, equipment, operators, or the environment. Controlling variation is an essential step in realizing product quality. To successfully control variation, manufacturing firms rely on the measurement of carefully chosen parameters. Because measurement of the entire population of products or components is seldom possible or desirable, **samples** from the **population** are

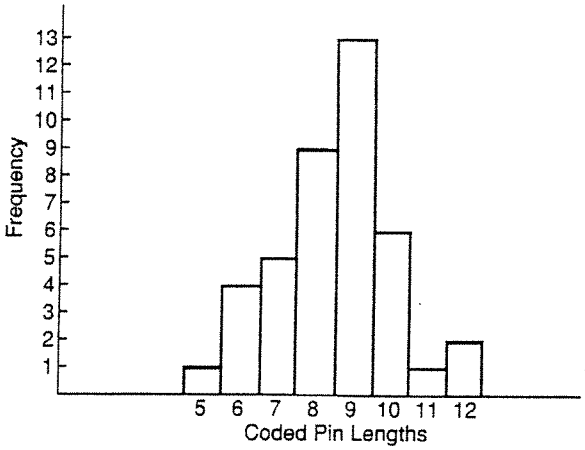


FIGURE 13.3 Coded pin lengths.

chosen. The extent to which sample data represent the population depends largely on such items as sample size, method of sampling, and time-dependent variations.

Measured data from samples taken during a manufacturing process can be plotted in order to determine the shape of the **frequency distribution.** The frequency distribution can give a visual clue to the process average and dispersion. The latter is referred to as **standard deviation.** Figure 13.3 shows a frequency distribution plot of 40 coded pin lengths expressed in thousands of an inch above 1 inch. Thus, the coded length 6 represents an actual length of 1.006 in. For the data shown, average coded pin length is 8.475 and standard deviation is 1.585.

Normal Distribution

Although there is an infinite variety of frequency distributions, the variation of measured parameters typically found in the manufacturing industry follows that of the normal curve. The normal distribution is a continuous bell-shaped plot of frequency vs. some parameter of interest and is an extension of a histogram whose basis is a large population of data points. Figure 13.4 shows a normal distribution plot superimposed on a histogram. Some important properties of the normal distribution curve are

1. The distribution is symmetrical about the population mean μ.
2. The curve can be described by a specific mathematical function of population mean μ and population standard deviation σ.

An important relationship exists between standard deviation and area under the normal distribution curve. Such a relationship is shown in Fig. 13.5 and may be interpreted as follows: 68.26% of the readings (or area under the curve) will be between $\pm 1\sigma$ limits, 95.46% of the readings will be between $\pm 2\sigma$ limits, and 99.73% of the readings will be between $\pm 3\sigma$ limits. The significance of this relationship is that the standard deviation can be used to calculate the percentage of the population that falls between any two given values in the distribution.

Statistical Quality Control

Statistical quality control (SQC) deals with collection, analysis, and interpretation of data to monitor a particular manufacturing or service process and ensure that the process remains within its capacity. In order to understand process capability, it is necessary to realize that variation is a natural phenomenon that will occur in any process. Parts will appear identical only due to the limitation of the inspection or measurement instrument. The sources of these variations may be the material, process, operator, time of the operation, or any other significant variables. When these factors are kept constant, the minor

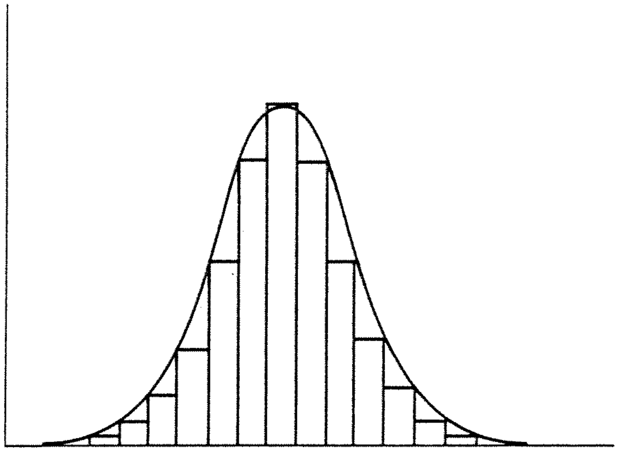


FIGURE 13.4 Normal distribution curve.

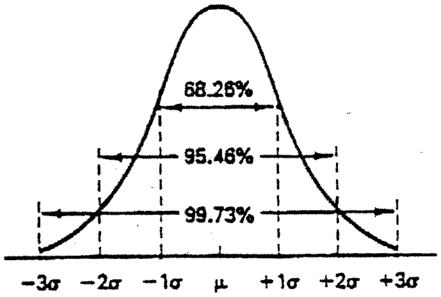


FIGURE 13.5 Percentages under the normal curve.

variations inherent in the process are called *natural* (or *chance*) *variations*, as opposed to variations due to **assignable causes.**

Control charts are utilized to determine when a given process variation is within the expected or natural limits. When the magnitude of variation exceeds these predetermined limits, the process is said to be *out of control.* The causes for out-of-control conditions are investigated and the process is brought back in control. Control charts or the control limits for the natural or chance-cause variations are constructed based on the relationship between the normal distribution and the standard deviation of the distribution. As stated earlier, since approximately 99.73% of a normal distribution is expected to fall between $\pm 3\sigma$ of the distribution, control limits are established at $\overline{X} \pm 3\sigma$ for the process. Therefore, any sample taken from the process is expected to fall between the control limits or the $\overline{X} \pm 3\sigma$ of the process 99.73% of the time. Any sample not within these limits is assumed to indicate an out-of-control condition for which an assignable cause is suspected.

Control charts can be divided into two major categories: control charts for variables (measureable quality characteristics, i.e., dimension, weight, hardness, etc.) and control charts for attributes (those quality characteristics not easily measurable and therefore classified as conforming or not conforming, good or bad, etc.).

Control Charts for Variables

The most common charts used for variables are the $\overline{X}$ and R charts. The charts are used as a pair for a given quality characteristic. In order to construct control charts for variables, the following steps may be followed:

1. Define the quality characteristic that is of interest. Control charts for variables deal with only one quality characteristic; therefore, if multiple properties of the product of the process are to be monitored, multiple charts should be constructed.
2. Determine the sample (also called the *subgroup*) size. When using control charts, individual measurements or observations are not plotted, but, rather, sample averages are utilized. One major reason is the nature of the statistics and their underlying assumptions. Normal statistics, as the term implies, assumes a normal distribution of the observations. Although many phenomena may be normally distributed, this is not true of all distributions. A major statistical theory called the *central limit theorem* states that the distribution of sample averages will tend toward normality as the sample size increases, regardless of the shape of the parent population. Therefore, plotting sample averages ensures a reasonable normal distribution so that the underlying assumption of normality of the applied statistics is met.

   The sample size (two or larger) is a function of cost and other considerations, such as ease of measurement, whether the test is destructive, and the required sensitivity of the control charts. As the sample size increases, the standard deviation decreases; therefore, the control limits will become tighter and more sensitive to process variation.
3. For each sample calculate the sample average, $\overline{X}$, and the sample **range**. For each sample record any unusual settings (e.g., new operator or problem with raw material) that may cause an out-of-control condition.
4. After about 20 to 30 subgroups have been collected, calculate

   $$\overline{\overline{X}} = \frac{\sum \overline{X}}{g}; \quad \overline{R} = \frac{\sum R}{g}$$

   where $\overline{X}$ is the average of averages, $\overline{R}$ is the average of range, and g is the number of samples or subgroups.
5. Trial upper and lower control limits for the $\overline{X}$ and R chart are calculated as follows:

   $$\mathrm{UCL}_{\overline{X}} = \overline{\overline{X}} + A_2\overline{R}; \quad \mathrm{UCL}_R = D_4\overline{R}$$

   $$\mathrm{LCL}_{\overline{X}} = \overline{\overline{X}} - A_2\overline{R}; \quad \mathrm{LCL}_R = D_3\overline{R}$$

   A_2, D_3, and D_4 are constants and are functions of sample sizes used. These constants are used to approximate process standard deviation from the range. Tables of these constants are provided in Banks [1989], De Vor et al. [1992], Grant and Leavenworth [1988], and Montgomery [1991].
6. Plot the sample averages and ranges on the $\overline{X}$ and the R chart, respectively. Any out-of-control point that has an assignable cause (new operator, etc.) is discarded.
7. Calculate the revised control limits as follows:

   $$\overline{X}_o = \frac{\sum \overline{\overline{X}} - \sum \overline{\overline{X}}_d}{g - g_d}; \quad R_o \frac{\sum R - \sum R_d}{g - g_d}; \quad \sigma_o = \frac{R_o}{D_2}$$

   $$\mathrm{UCL}_{\overline{X}_o} = \overline{\overline{X}}_o + A\sigma_o \quad \mathrm{UCL}_R = D_2\sigma_o$$

   $$\mathrm{LCL}_{\overline{X}_o} = \overline{\overline{X}}_o - A\sigma_o \quad \mathrm{LCL}_R = D_1\sigma_o$$

The subscript o and d stand for revised and discarded terms, respectively. The revised control charts will be used for the next production period by taking samples of the same size and plotting the sample average and sample range on the appropriate chart. The control limits will remain in effect until one or

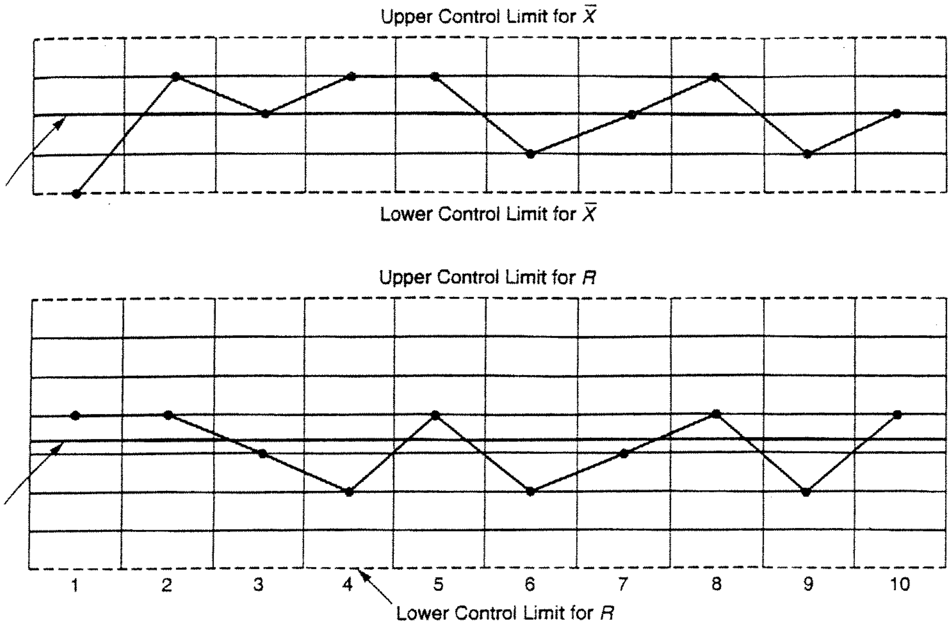


FIGURE 13.6 Control charts for $\bar{X}$ and R.

more factors in the process change. Figure 13.6 shows control charts of $\bar{X}$ and R values for ten subgroups. Each subgroup contained five observations because none of the ten data points lie outside of either upper and lower control limits; the process is designated "in control".

The control charts can be used to monitor the out-of-control conditions of the process. It is imperative to realize that patterns of variation as plotted on the charts should give clear indications to a process that is headed for an out-of-control condition or one that displays an abnormal pattern of variations. Whereas no point may actually fall out of the limits, variation patterns can often point to some unusual process behavior that requires careful study of the process.

Control Charts for Attributes

For those quality characteristics that are not easily measured — or in such cases where count of defects of defective items are involved or go-no-go gauges are used — control charts for attributes are used. These charts can be grouped into two major categories:

1. Charts for defectives or nonconforming items
2. Charts for defects or nonconformities

Charts for Nonconforming Items

The basic charts in this group are the fraction **nonconforming** chart (p chart), percent nonconforming chart ($100p$ chart), and the count of nonconforming chart (np chart). The procedure for the construction, revision, and the interpretation of control charts for attributes is similar to that for $\bar{X}$ and R charts. The following steps may be used to construct a p chart:

1. Once sample size has been established, fraction nonconforming, p, is determined for each sample by

$$p = \frac{np}{n}$$

where n is the sample size and np is the count of defectives or nonconforming items in the sample.

2. After roughly 20 to 30 subgroups have been collected, calculate $\bar{p}$, the value of the central line, or the average fraction defective.

$$\bar{p} = \frac{\sum np}{\sum n}$$

3. Trial control limits are calculated using:

$$\text{UCL} = \bar{p} + 3\sqrt{\frac{\bar{p}(1-\bar{p})}{n}}$$

$$\text{LCL} = \bar{p} - 3\sqrt{\frac{\bar{p}(1-\bar{p})}{n}}$$

4. Plot the fraction defective for each subgroup. The out-of-control subgroups that have assignable causes are discarded, and revised limits are calculated as follows:

$$p_o = \frac{\sum np - \sum np_d}{\sum n - n_d}$$

$$\text{UCL} = p_o + 3\sqrt{\frac{p_o(1-p_o)}{n}}$$

$$\text{LCL} = p_o - 3\sqrt{\frac{p_o(1-p_o)}{n}}$$

5. If the lower control limit is a negative number, it is set to zero. Sample points that fall above the upper limit indicate a process that is out of control. However, samples that fall below the lower limit, when the lower control limit is greater than zero, indicate a product that is better than expected. In other words, if a sample contains fewer nonconforming items than the process is capable of producing, the sample fraction defective will fall below the lower control limit. For this reason some practitioners may choose to set the lower limit of the attribute charts to zero. This practice, however, may mask other problems or potentials for process improvements.

Other charts for nonconforming items are simple variations of the p chart. In the case of the $100p$ chart, all values of the p chart are expressed as percentages. In the case of the np chart, instead of plotting fraction or percent defectives, actual counts of nonconforming or defective items are plotted. See Banks [1989], De Vor et al. [1992], Grant and Leavenworth [1988], and Montgomery [1991] for greater detail. The formulas for the central line and the control limits for an np chart are given below. It is assumed that the revised value for universe fraction defective, p, is known. If p is not known, then the procedure for the p chart must be carried out to determine the revised value for the universe fraction defective.

$$\text{Central line} = np_o$$

$$\text{Control limits} = np_o \pm 3\sqrt{np_o(1-p_o)}$$

where n is the sample size and p_o is the universe fraction defective.

Charts for Defects or Nonconformities

Whereas the charts for defective or nonconforming items are concerned with the overall quality of an item or sample, charts for defects look at each defect (i.e., blemish, scratch, etc.) in each item or sample. One may consider an item a nonconforming item based on its overall condition. A defect or **nonconformity** is that condition that makes an item a nonconforming or defective item.

In this category are *c* charts and *u* charts. The basic difference between the two is the sample size. The sample size, n, for a *c* chart is equal to one. In this case the number of nonconformities or defects are counted per a single item. For a *u* chart, however, $n > 1$. See Banks [1989], De Vor et al. [1992], Grant and Leavenworth [1988], and Montgomery [1991] for the formulas and construction procedures.

Tolerances and Capability

As stated earlier, *process capability* refers to the range of process variation that is due to chance or natural process deviations. This was defined as $\bar{X} \pm 3\sigma$ (also referred to as 6σ), which is the expected or natural process variation. **Specifications** or **tolerances** are dictated by design engineering and are the maximum amount of acceptable variation. These specifications are often stated without regard to process spread. The relationships between the process spread or the natural process variation and the engineering specifications or requirements are the subject of process capability studies. Process capability can be expressed as

$$C_p = \frac{\mathrm{US} - \mathrm{LS}}{6\sigma}$$

where C_p = process capability index, US = upper engineering specification value, and LS = lower engineering specification value.

A companion index, C_{pk}, is also used to describe process capability, where

$$C_{pk} = \frac{\mathrm{US} - \bar{X}}{3\sigma}$$

or

$$C_{pk} = \frac{\bar{X} - \mathrm{LS}}{3\sigma}$$

The lesser of the two values indicates the process capability. The C_{pk} ratio is used to indicate whether a process is capable of meeting engineering tolerances and whether the process is centered around the target value $\bar{X}$. If the process is centered between the upper and the lower specifications, C_p and C_{pk} are equal. However, if the process is not centered, C_{pk} will be lower than C_p and is the true process capability index. See De Vor et al. [1992], Grant and Leavenworth [1988], and Montgomery [1991] for additional information.

A capability index less than one indicates that the specification limits are much tighter than the process spread. Hence, although the process may be in control, the parts may well be out of specification. Thus, the process does not meet engineering requirements. A capability index of one means that, as long as the process is in control, parts are also in spec. The most desirable situation is to have a process capability index greater than one. In such cases, not only are approximately 99.73% of the parts in spec when the process is in control, but, even if the process should go out of control, the product may still be within the engineering specifications. Process improvement efforts are often concerned with reducing the process spread and, therefore, increasing the process capability indices.

An extremely powerful tool for isolating and determining those factors that significantly contribute to process variation is statistical design and analysis of experiments. Referred to as "design of experiments", the methodology enables the researcher to examine the factors and determine how to control these factors in order to reduce process variation and therefore increase process capability index. For greater detail, see Box et al. [1978].

Defining Terms

Assignable causes: Any element that can cause a significant variation in a process.

Frequency distribution: Usually a graphical or tabular representation of data. When scores or measurements are arranged, usually in an ascending order, and the occurrence (frequency) of each score or measurement is also indicated, a frequency distribution results.

No. of Defectives	Frequency
0	10
1	8
2	7
3	8
4	6
5	4
6	2
7	1
8	1
9	0

The frequency distribution indicates that ten samples were found containing zero defectives.

Nonconforming: A condition in which a part does not meet all specifications or customer requirements. This term can be used interchangeably with *defective.*

Nonconformity: Any deviation from standards, specifications, or expectation; also called a *defect.* Defects or nonconformities are classified into three major categories: critical, major, and minor. A critical nonconformity renders a product inoperable or dangerous to operate. A major nonconformity may affect the operation of the unit, whereas a minor defect does not affect the operation of the product.

Population: An entire group of people, objects, or phenomena having at least one common characteristic. For example, all registered voters constitute a population.

Quality: Quality within the framework of manufacturing is defined as conformance to requirements.

Range: A measure of variability or spread in a data set. The range of a data set, R, is the difference between the highest and the lowest values in the set.

Sample: A small segment or subgroup taken from a complete population. Because of the large size of most populations, it is impossible or impractical to measure, examine, or test every member of a given population.

Specifications: Expected part dimensions as stated on engineering drawings.

Standard deviation: A measure of dispersion or variation in the data. Given a set of numbers, all of equal value, the standard deviation of the data set would be equal to zero.

Tolerances: Allowable variations in part dimension as stated on engineering drawings.

References

ASQC. *Malcolm Baldridge National Quality Award — 1994 Award Criteria,* American Society for Quality Control, Milwaukee, WI, 1994.

Banks, J. *Principles of Quality Control,* John Wiley & Sons, New York, 1989.

Box, G. E. P., Hunter, W. G., and Hunter, J. S. *Statistics for Experimenters,* John Wiley & Sons, New York, 1978.

De Vor, R. E., Chang, T. H., and Sutherland, J. W. *Statistical Quality Design and Control,* Macmillan, New York, 1992.

Grant, E. L. and Leavenworth, R. S. *Statistical Quality Control, 6th ed.,* McGraw-Hill, New York, 1988.

Lamprecht, J. L. *Implementing the ISO 9000 Series,* Marcel Dekker, New York, 1993.

Montgomery, D. C. *Statistical Quality Control, 2nd ed.,* John Wiley & Sons, New York, 1991.

Saylor, J. H. *TQM Field Manual,* McGraw-Hill, New York, 1992.

Further Information

Statistical Quality Control, by Eugene Grant and Richard Leavenworth, offers an in-depth discussion of various control charts and sampling plans.

Statistics for Experimenters, by George Box, William Hunter, and Stewart Hunter, offers an excellent and in-depth treatment of design and analysis of design of experiments for quality improvements.

Most textbooks on statistics offer detailed discussions of the central limit theorem. *Introduction to Probability and Statistics for Engineers and Scientists,* written by Sheldon Ross and published by John Wiley & Sons, is recommended.

American Society for Quality Control, P.O. Box 3005, Milwaukee, WI 53201-3005, phone: (800)248-1946, is an excellent source for reference material, including books and journals, on various aspects of quality.

13.6 Experience Curve

James P. Gilbert

Interest in organizational experienced-based learning is at an all-time high. The work of Peter Senge [1990] in his critically acclaimed book *The Fifth Discipline* has been read by many organizational leaders and found to be useful in improving their organizations. Senge invites us to use a holistic process of improvement that includes systems thinking, personal mastery, mental models, shared vision, and team learning.

The focus here is on a more narrow thrust of individual learning through personal experience. The **experience curve** is sometimes incorrectly used interchangeably with these terms: learning curve, progress curve, improvement curve, and startup curve. There is a hierarchy of concepts from the more global experience curve to the more operational level of learning curve. The concepts of experience and learning curves are very popular in business organizations and serve an important function in providing conviction and confidence to the vague notion of learning by doing [Hall and Howell, 1985].

The Experience Curve Logic

The terms experience curve and **learning curve** are occasionally taken to mean the same thing. These curves are both strategic and tactical tools useful in quantifying the rate at which cumulative experience allows a reduction in the amount of productive resources the firm must expend to complete its desired tasks [Melnyk and Denzler, 1996]. It is possible and indeed helpful to distinguish between them. The experience curve is broader in scope and refers to the reduction of costs that may occur over the life of a product, i.e., total costs [Hall and Howell, 1985]. The experience curve is based on the economic theory known as "economies of scale". The Boston Consulting Group empirically confirmed this effect with studies from many industries. Figure 13.7 illustrates the general shape for the experience curve where the decrease in average unit costs varies between 20 and 30% with each doubling of volume. Volume is a surrogate for accumulated experience and learning is a consequence [Starr, 1996]. With several iterations of doubling, the curve "flattens out" as most of the learning benefits have occurred. Thus, potential benefits for capacity, price, and market share implications are obtained in early iterations of productive doubling.

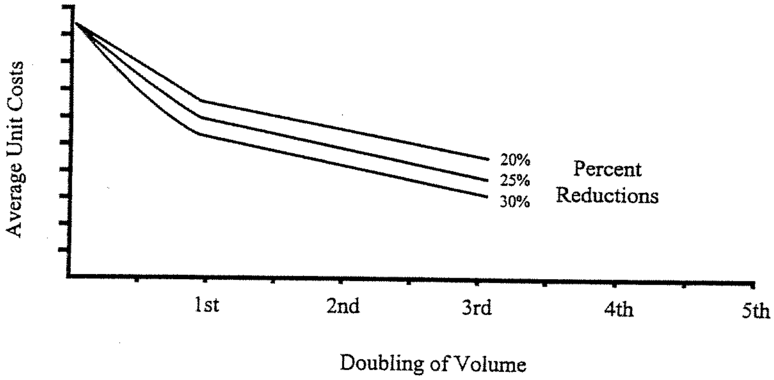


FIGURE 13.7 Average unit costs decrease with increasing experience. (Source: Starr, M. K. *Operations Management: A Systems Approach*, p. 431, Southwestern Publishing, Danvers, MA, 1996. With permission.)

The learning curve usually refers to a more micro concept employed in work analysis and cost control. Learning curve embodies the idea of learning by doing. These terms, experience curve and learning curve, differ in respect to the costs covered, the amount of productive output during the period of learning, and the causes of cost reduction [Hall and Howell, 1985].

The intuitive nature of the experience curve might mean that people frequently use this concept when repetitive actions improve results. For example, experience curve phenomena may have played a large role in the planning of the construction of the great pyramids of Egypt. The analytical use of the concept for business purposes first surfaced in airplane construction where Wright [1936] observed that, as the quantity of manufactured units doubled, the number of direct labor hours needed to produce each individual unit decreased at a uniform rate. This observation had strategic and operational importance for the development of aircraft. He illustrated the variation of labor cost with production quantity in the formula

$$F = \mathrm{Log}\, F/\mathrm{Log}\, N \qquad (1)$$

where F = a factor of cost variation proportional to the quantity N. The reciprocal of F then represents a direct percent variation of cost vs. quantity [Wright, 1936].

Wright shows that experience-based efficiencies in unit output are closely correlated with cumulative output and go beyond changes in design and tooling. This work presents evidence that as unit volume for a particular item increases there are predictable corresponding reductions in cost. These data then become central concepts for strategic and operational planning.

Experience Curve Principles

At the strategic planning level, the experience curve follows a profit enhancement desire via an increased market share strategy. It may be hoped that, by increasing market share while reducing costs, a detriment to market entrants will ensue [Lieberman, 1989]. Learning through experience becomes an important component of the increased market share strategy, hopefully leading to increased profits (see Fig. 13.8). This influence charts shows the underlying logic of the use of the experience curve. Quality learning is enhanced through the shared experience at the worker level and the organizational level. The critical aspect of quality products along with movement along the experience curve increases the time available for work, thus increasing productive efficiency. As the individual employees and the organization become more efficient, there should be a corresponding increase in productivity. More output for less input effectively increases capacity, which taken together with the increased efficiency and productivity should lead to a reduction in unit cost. The business is investing in a cost leadership posture based on the

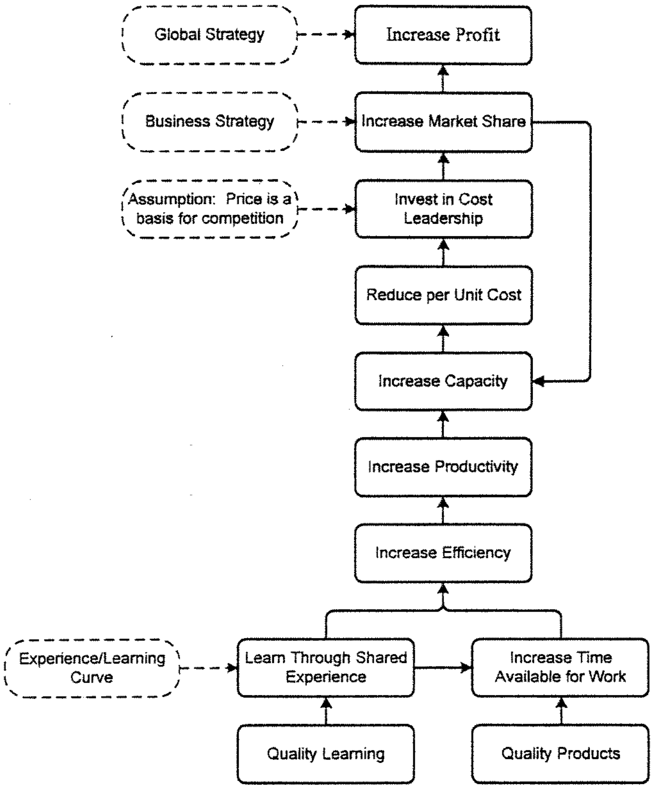


FIGURE 13.8 Influence chart of the experience curve strategy and application.

assumption that price is a basis for competition. If the firm is able to produce quality units and reduce market price, there is the opportunity for increased market share (the business strategy). Increased market share via a reduced price may lead to the global goal of improving profitability.

Generally, then, we see that the use of the cost leadership strategy using the experience curve is based on several assumptions [Amit, 1986]:

1. Price is a basis for competition.
2. If per unit cost is reduced, price may be reduced, which may lead to increased market share.
3. As cumulative output increases, the firm's average cost is reduced. Therefore, for any production rate, there is a reduction in the per-unit cost.
4. If market share is increased, profits will increase.

Note that another critical assumption of the experience curve is that learning can be kept within the organization [Lieberman, 1989]. Where industry-wide dissemination of process technology is rapid, the benefits of organizational learning through the experience curve may be short lived. The cost benefits, therefore, may not lead to increased market share even though industry costs are declining because all participants are learning at approximately the same rate.

Learning Curve Formulation

The formulation for the learning curve model is commonly shown in one of two ways: as a margin cost model and as a direct labor hour model. Both derivations are shown here for clarity, but the direct labor hours formulation may be more useful as hourly compensation typically changes over time and there may be inflation considerations as well. Also, direct labor hours may be easily converted into costs if necessary [Yelle, 1979]. By convention, we refer to experience curves by the complement of the improvement rate. For example, a 90% learning curve indicates a 10% decrease in per-unit (or mean) time or cost with each doubling of productive output. Experience and learning curves normally apply only to cost of direct labor hours.

Marginal Cost Model

The cumulative-average learning curve formulation is

$$y_{cx} = ax^{-b} \tag{2}$$

where y_{cx} = the average cost of the first x units, a = the first unit cost, x = the cumulative unit number output, and b = the learning "elasticity", which defines the slope of the learning curve.

This learning curve model indicates that, as the quantity of units produced doubles, the average cost per unit decreases at a uniform rate.

Direct Labor Hours Model

$$Y = KX^{n} \tag{3}$$

where Y = the number of direct labor hours required to produce the Xth unit, K = the number of direct labor hours required to produce the first unit, X = the cumulative unit number, $n = \log \phi/\log 2$, ϕ = the learning rate, and $1-\phi$ = the progress ratio.

These empirical models have been shown to fit many production situations very well. We must be cautious, however, as there are many other variables at work at the same time as the experience curve is being utilized. For example, production factors such as product design decisions, selection of tooling and equipment, methods analysis and layout, improved organizational and individual skills training, more effective production scheduling and control procedures, and improved motivation all play a role in decreasing cost and increasing capacity.

Applications and Uses

There are three general areas for the application and use of experience curves (see Table 13.7). As can be seen, there are numerous applications for the learning curve phenomenon. The usefulness depends on a number of factors: the frequency of product innovation, the amount of direct labor vs. machine paced output, and the amount of advanced planning of methods and tooling, all leading to a predictable rate of reduction in labor time.

Cautions and Criticisms

Abernathy and Wayne [1974] caution that the learning curve use needs to be managed in relation to firm innovation. This study of Ford Motor Company data illustrates that dependence on the learning curve phenomenon affects product innovation both in the nature of changes and the intensity of innovation activity. It should noted that the authors studied the model T Ford, which had a long life cycle. It is unlikely that we will see such long product lives today. The authors are not arguing that the use of the learning curve is inappropriate but rather that small innovative firms are having problems transitioning to repetitive, cost efficient, experienced-based manufacturing. The key point drawn from the study is that "there must be a theoretical limit to the amount by which costs can ultimately be reduced, a manufacturer reaches the practical limit first" [Abernathy and Wayne, 1974]. Caution, then, is necessary as management balances increasing competition, as competitors discover the process methods of the leader, and the firm's decreasing ability to be innovative, as dependence on cost reduction continues.

As with all data-driven decision tools, the selection of appropriate input data must be chosen wisely. The cautions described by Andress [1954] are still important today. Experience curve conclusions may be erroneous if the labor hour data are not correct. For example, if increased purchased components are

TABLE 13.7 Experience Curve: Applications and Uses

Strategic	Internal	External
Determine volume-cost changes	Develop labor standards	Estimate actual purchase costs
Estimate new product startup costs	Calculate rates of material supply required	Supplier scheduling
Determine capital needs	Manpower planning	Budgeting for cash flow
Pricing of new products	Production scheduling	Purchased goods planning
	Budgeting	
	Inventory planning	
	Evaluate new employees during training	
	Develop efficiency measures	
	Develop costs per unit	
	Plan delivery schedules	
	Make or buy decisions	
	Equipment planning	
	Work flow planning	
	Capacity planning	
	Establish wage incentive plans	

being used, this shift in labor hours to the supplier may seem to increase experience-based savings. This may be illusionary as the same amount of labor time is being expended and therefore no net gain has been achieved. Changes in labor mix, be they internal or external to the firm, may cause inappropriate data interpretations.

These situations may also exist if considerable capital has been spent on new tooling, engineering, and methods planning. We cannot separate direct labor hours from other cost elements. As the learning curve is only considering direct labor, changes in overhead may distort the picture. Management's use of the experience curve is an attempt to increase productive capacity; however, if the production rate is increased through sales volume, it may be possible to increase throughput by reorganizing direct labor as a function of this increased volume. Again, it may seem that experience is achieving cost savings when it may well be extraordinary efforts from marketing and sales.

Economic Implications

The experience curve continues to be a popular and useful tool for planning, budgeting, and controlling productive resources leading to increased profitability. Empirical evidence is mixed on the validity of the method. What appears to be unchallenged is that management continues to find the tool useful. This belief adds conviction and confidence to decision making and is certainly valuable in that light. With current thrusts for speed, flexibility, and ever-shortening product life cycles, it may be thought that experience curves are no longer necessary. However, the evidence to date is that early advantages accrue to those firms who take advantage of experience-based cost savings before the competitors' industry knowledge catches up. This time and cost advantage may lead to significant gains in market share, which will be difficult for lagging firms to overcome.

Defining Terms

Experience curve: An analytical tool designed to quantify the rate at which experience of accumulated output to date affects total lifetime costs. This term is broader than **learning curve** in respect to the costs covered, the range of output during which the reductions in costs take place, and the causes of cost reduction. (Adapted from Hall and Howell [1985] and Starr [1996]).

Learning curve: An analytical tool designed to quantify the rate at which cumulative-experience of labor hours or cost allows an organization to reduce the amount of resources it must expend to accomplish a task. This function is usually described as with each doubling of productive unit output, the time per unit decreases at a predictable rate (Adapted from Melnyk and Denzler [1996]).

References

Abernathy, W. J. and Wayne, K. Limits of the learning curve, *Harv. Bus. Rev.*, 52: 109–119, 1974.

Amit, R. Cost leadership strategy and experience curves, *Strat. Mgt. J.*, 7: 281–292, 1986.

Andress, F. J. The learning curve as a production tool, *Harv. Bus. Rev.*, (Jan.-Feb.): 87–97, 1954.

Hall, G. and Howell, S. The experience curve from the economist's perspective, *Strat. Mgt. J.* 6: 197–212, 1985.

Lieberman, M. B. The learning curve, technology barriers to entry, and competitive survival in the chemical processing industries, *Strat. Mgt. J.* 10: 431–447, 1989.

Melnyk, S. A. and Denzler, D. R. *Operations Management: A Value-Driven Approach*, Richard D. Irwin, Chicago, 1996.

Senge, P. M. *The Fifth Discipline: The Art and Practice of the Learning Organization*, Doubleday Currency, New York, 1990.

Starr, M. K. *Operations Management: A Systems Approach*, Boyd & Fraser, Danvers, MA, 1996.

Wright, T. P. Factors affecting the cost of airplanes, *J. Aeronaut. Sci.*, 3(4): 122–128, 1936.

Yelle, L. E. The learning curve: historical review and comprehensive survey, *Dec. Sci.*, 10: 302–328, 1979.

For Further Information

For a nice overview of the development of the learning curve over time, the series published by the Harvard Business Review is excellent: *The Learning Curve as a Production Tool* (Jan.-Feb., 1954) by Frank J. Andress; *Profit from the Learning Curve* (Jan.-Feb., 1964) by Alfred B. Hirschmann, and *Limits of the Learning Curve* (Sept.-Oct., 1974) by William J. Abernathy and Kenneth Wayne.

13.7 Just-in-Time Purchasing

James P. Gilbert

Management of technology exists today within a business climate where manufacturers and service providers are driven by a passion for satisfying customers. We enhance the customers' lives by creating products and services that satisfy needs and wants as well as solve problems. Therefore, technology companies are looking for ever-increasing speed from the point of new product or service conceptualization to market availability for customers. Speed and flexibility of product offerings are aided by technology and drive new technology initiatives.

Product and service providers are increasingly becoming assemblers of items purchased from suppliers, as opposed to fabricators of significant numbers of parts. The make/buy decision is moving to the purchase side. We are buying the quality, process capability, and expertise of suppliers. Suppliers become critical to the success of our businesses and to the success of our efforts to deliver with speed and flexibility to our ultimate consumers. **Just-in-time (JIT) purchasing** develops the buyer/supplier relationships through true partnerships that aid both parties to increase profit performance and develop market share domination.

We are told by the National Academy of Engineering that there are eight major needs in the management of technology [McGaughey, 1989]:

- How to integrate technology into the overall strategic objectives of the firm.
- How to get into and out of technology faster and more effectively.
- How to assess/evaluate technology more effectively.
- How to best accomplish technology transfer.
- How to reduce new product development time.
- How to manage large, complex, and interdisciplinary or interorganizational projects.
- How to manage the organization's internal use of technology.
- How to leverage the effectiveness of technical professionals.

TABLE 13.8 Just-in-Time Purchasing Characteristics

Suppliers	Quantities
A few, nearby suppliers	Steady output rate (a desirable prerequisite)
Repeat business with same suppliers	Frequent deliveries in small lot quantities
Active use of analysis to enable desirable suppliers to become/stay price competitive	Delivery quantities variable from release to release but fixed for whole contract term
Clusters of remote suppliers	Long-term contract agreements
Competitive bidding mostly limited to new part numbers	Suppliers encouraged to reduce their production lot sizes
Buyer plant resists integration of supplier business	Little or no permissible overage of receipts
Suppliers encouraged to extend JIT buying to their suppliers	Suppliers encouraged to package in exact quantities
	Minimal release paperwork
Quality	Shipping
Minimal product specifications imposed on supplier	Use of company-owned or contract shipping, contract warehousing, and trailers for freight consolidation/storage where possible
Suppliers helped to meet quality specifications	Scheduling of inbound freight by buyer
Close relationships between buyers' and suppliers' quality assurance people	
Suppliers encouraged to use statistical process control instead of lot sampling inspection	

Source: Schonberger, R. J. and Gilbert, J. P. *Calif. Mgt. Rev.*, 26(1): 58, 1983.

JIT purchasing plays an important role in the accomplishment of these objectives by developing buyer/supplier relationships from the raw material suppliers, midlevel value-added suppliers, our firm's quality processes, and on to the final customer. Some have suggested that JIT purchasing is just a way of pushing inventory down the supply chain. Nothing could be further from the truth. The goal is to make the entire chain lean and efficient from supplier to customer to the next supplier and on to the ultimate customer so that speed and flexibility are integrated throughout the fabrication and service systems.

Fundamentals of JIT Purchasing

The major challenge facing purchasers in technology-driven companies is to proactively respond to multiple demands for (1) quality performance, (2) purchasing and inventory management through manufacturing resource planning and JIT production, (3) buyer-supplier partnerships, and (4) electronic data interchange [Farrell, 1990]. Purchasing professionals continue to apply the most sophisticated techniques in close cooperation with both the using departments and suppliers.

An emergence of purchasing's use of JIT was noticeable in the literature in the early 1980s. The term "JIT purchasing" was coined by Schonberger and Gilbert [1983] where the authors explained Japanese JIT purchasing practices and their benefits and showed that, despite obstacles, these practices could work in Western companies. Hahn [1983] provided an overview of the JIT approach (including purchasing) used by the Japanese and also highlighted the impact that JIT's implementation might have on the purchasing function in U.S. firms. Today, many Western firms have switched from traditional purchasing practices to the JIT purchasing concept [Lee and Ansari, 1986].

A number of characteristics of JIT purchasing are listed in Table 13.8. The JIT characteristics are interrelated and illustrated with four groups: suppliers, quantities, quality, and shipping.

Buyer/Supplier Partnership

The buyer/supplier partnership is the process and product of merging efforts to be responsive to each other's needs while conducting business in a way that provides maximum potential for growth and profit by both parties. This definition implies (1) communicating and planning as a team, (2) setting up and implementing a sourcing policy that makes sense to the buyer and the responsive suppliers, (3) fostering the building of long-term relationships, (4) emphasizing reduction of buyers' and suppliers' costs, not prices, and (5) the embodiment of JIT purchasing principles to improve continuously both parties' purchasing practices.

The primary underlying factors that describe a JIT partnership-oriented, buyer-supplier relationship are

1. Improved joint communication and planning efforts.
2. Improved responsiveness of receiving incoming purchased items benefiting both parties.
3. A sourcing policy beneficial to both, usually single or dual sourcing.
4. A more win-win approach to agreements and negotiations exchange whereby a mutually beneficial approach to the negotiations and the follow-up working relationship is enhanced.
5. Reducing costs for buyer and supplier — reduce both parties' costs and get better-quality processes and products moving through both systems.
6. Less concern with buyer's price — gaining the lowest price does not necessarily take the supplier's interests and needs into account.
7. Apply a concerted effort to use joint buyer/supplier efforts to improve relationships.
8. Become educated, involved in, and committed to increased use of JIT purchasing.

Improved Joint Communication and Planning Efforts

There is a need for improved joint communication and enhanced joint planning efforts between buyers and suppliers. Many buyers have recognized this and are experimenting with tighter integration with supplier planning and scheduling systems. Recently, electronic data interchange (EDI) has gathered momentum and has become the backbone of communications. This computer-to-computer communication interface eliminates dependence on the mail by allowing instant transmission of business documents. This has greatly enhanced many purchasing departments as EDI is the link between the company and its suppliers. Its role as the prime communication channel cannot be overemphasized.

Improved Responsiveness of Receiving

These aspects of the definition of the buyer/supplier partnership relationship deals with the buyer's response once purchased parts enter the receiving area. The importance of an integrated approach to the flow of both materials and information from the supplier to the buyer is crucial.

One of the first priorities of any plant should be to improve incoming product quality. Rather than attempting to inspect quality into a product, managers today must design and then purchase quality into the product. However, in order to meet the demand for more frequent delivery schedules and for zero-defect parts, and to decrease risk and uncertainty, companies must be willing to make long-term commitments, share engineering changes, supply the vendors with delivery schedules, and exchange product expertise. Improved quality benefits both buyer and supplier, as do reduced inspections. The quest for quality is a key ingredient in the sourcing policy of the buyer.

Beneficial Sourcing Policy

The first step in selecting suppliers is to identify all potential sources that appear capable of supplying the position. Deming [1986] believed that firms are better off with a single-source supplier. However, most manufacturers traditionally have preferred to work with multiple suppliers for fear that single sourcing could result in supply disruption.

While single sourcing offers some excellent opportunities for reducing costs and gaining control of purchases, there are some potential problem areas. These include the erosion of the supplier base for the buyer and, for the supplier, loss of technological thrust, excess control, and loss of supplier identity. Many manufacturers are reducing their number of suppliers so as to control quality, and they will give preference to those close to home. Small manufacturers feel less isolated because large companies are involved in their problems. A company can achieve enhanced performance from its suppliers by reducing their number and creating full partnerships that are supported by management commitment and trust on both sides. As a true partner, a buyer and supplier will attempt to reach more positive, jointly beneficial agreements.

Win-Win Approach to Agreements and Negotiations

One of the more prevalent attributes of a JIT purchasing partnership arrangement is a long-term relationship. With JIT purchasing, it is far more profitable and reliable to develop long-term relationships in which suppliers are partners, not victims. The result is a "win-win" situation for buyer and supplier. Long-term commitments providing exceptionally good communications also provide a strong understanding of the business. Garnering those fewer but better suppliers is a crucial issue that some authors believe is vital to beginning a partnership arrangement with a supplier. Hahn et al. [1990] conclude that it is necessary to plan carefully and select competent suppliers in terms of quality, delivery, and cost capabilities. One essential task in setting up JIT is to integrate the suppliers into the overall strategy. Therefore, the process of vendor evaluation and selection is a time-consuming and critical aspect of establishing partnerships. A stronger partnership between manufacturers and suppliers is needed if purchased components are to be delivered to assembly lines ready for production, in exact quantities needed, and with zero defects (please see the section below on supplier certification).

The adversarial nature of face-to-face confrontations changes in a partnership-oriented relationship. Agreements based on competitive bidding using short-term contracts do little to fortify strong working relationships between the buyer and supplier. Furthermore, not attempting to gain the "upper hand" in negotiations is key to negotiating with a partner. This entails using joint problem solving and the desire to reach a win-win approach whereby every negotiation participant leaves the table with an agreement that both parties are comfortable with. One way to reach a win-win situation is through joint efforts to decrease buyer and supplier costs.

Reducing Costs for Buyer and Supplier

As buyers and suppliers work together in partnership to improve quality, they will inevitably find that prices and costs go down for both the buyer and the supplier. Executives believe that purchasing is no longer just a process of buying things at the best price. Rather, purchasing has evolved into a whole new management profession. Buying solely on the basis of the lowest price can often be one of the worst vendor selection decisions. Many buyers are choosing vendors on the least total cost method, which is based on their quality, on-time delivery, technical design coordination, sales representatives' assistance, product training workshops, and other factors (including price). In 1988, NCR Corporation was chosen as the sixth winner of *Purchasing*'s Medal of Professional Excellence because of its enlightened approach to supplier relations and an emphasis on purchasing that shifted from price to value.

Less Concern with Buyer's Price

Many buyers are experimenting with various new approaches which are less "price" oriented, such as supplier base reduction and single or limited sourcing arrangements. Ishikawa [1986] claimed that at least 70% of the blame for defective purchased material lies with the purchasing organization driven by cost. Deming's [1986] view was that buyers have new responsibilities to fulfill, one of which is to end the practice of awarding business solely on price.

The lowest price embodies the philosophy of an adversarial-based approach to purchasing whereby the buyer wants the purchased items at the lowest price. Looking at this attribute from a supplier's standpoint, one would quickly conclude that to get the lowest price 100% of the time from the most qualified supplier may be difficult. The lowest price may not benefit both parties — it likely only serves the objectives of the buyer. This unilateral interest will likely erode any possibility of strong, long-term relationships.

Joint Buyer/Supplier Efforts to Improve Relationships

Much of the success of JIT is in the area of improved buyer/supplier relationships. Buyers benefit by having fewer suppliers to worry about and reduced labor in handling parts, while sellers benefit by concentrating on fewer and more productive sales calls. It is imperative to change the attitude that priorities and goals of the supplier are substantially different from those of the buyer, that buyers deal with many suppliers and change them frequently, and that buyer-seller transactions are random events with each transaction standing on its own.

Dobler et al. [1990] believe the most successful supplier management results when the buyer and the supplier view their relationship as a "partnership". Partnerships are based on mutual interdependency and respect. Respect permeates the partnership and replaces the adversarial attitudes present in too many buyer-supplier relationships.

Commitment is the most important factor in establishing good partnering agreements. However, because buyer-supplier relationships in the West have often been adversarial, we should be concerned that buyers will revert to former practices and drop suppliers after suppliers have made the necessary changes and investments to support JIT buyers.

The use of cooperative relationships with suppliers provides a method for purchasing managers to contribute positively to the strategic posture of their firms. They can do this by reducing the core supplier base to a few preferred suppliers and then by managing those suppliers accordingly. A close relationship with a supplier is possible if the company reduces the supplier base down to a manageable size. The real benefit of improved relationships with suppliers evolves from integrating them into the total business process of the company.

Education, Involvement, and Commitment to Increased Use of JIT Purchasing

Schonberger and Gilbert [1983] provide extensive lists of the positive impact that JIT purchasing can have upon an organization. For instance, Harley-Davidson reaped tremendous benefits after training its employees, management, and suppliers on JIT techniques. The employee is the key to the success of JIT purchasing implementation. Successful partnerships are built on a strong commitment to the importance of education in, and commitment to, the philosophy of JIT purchasing.

Supplier Certification

JIT purchasing partnership relationships often start with **supplier certification** programs. The processes of supplier certification are used to assure the customer that the supplier will consistently provide materials and processes that will meet and exceed all expectations and requirements. The strategy here is develop a win-win relationship between supplier and buyer which leads to increased market share, decreased costs, improved processes, quicker response times, increased reliability and conformance, and increased profits for both firms. Supplier certification is a joint effort of many skill areas within both firms. Often, the purchasing and quality assurance departments lead the effort, but engineering, marketing, and others are actively involved at various stages of the certification program.

The certification assessment process involves several in-depth, on-site investigations of the supplier's management expertise and practices as well as the overall stability of the supplier's business operations. The certification team will at a minimum review the supplier's: physical facilities, manufacturing capabilities, administrative systems, operating and order-processing systems, financial analysis, market data, customer satisfaction history, and technical support capabilities. Many detailed evaluations may occur during the certification process. Table 13.9 lists some of the areas of interest to the certifying firm.

The supplier certification team evaluates all data inputs relative to the decision and typically classifies suppliers into one of four categories: certified, conditionally certified, uncertified, and unevaluated. Supplier certification is an ongoing, never-ending process. Annual reviews are undertaken, as are periodic reviews as specific problems occur. These reviews must be satisfactory if the supplier is to maintain its certified status.

Conclusion

The rules, practices, and ideals are important to a JIT partnership among buyers and their suppliers. Without any one of them, the full potential may be more difficult to realize. Each purchasing organization should look inward before looking for help from its suppliers. If these eight underlying factors of a

TABLE 13.9 Supplier Certification Areas of Interest

Quality management processes	Quality history	Customer base	Quantity delivery history
Financial condition	Producibility	Cost control programs	Specification accuracy
On-time delivery record	Knowledgeable sales force	Education and training programs	Facilities and equipment
Labor conditions	Capacity availability and management	Market involvement	Organization of the firm
Research and development initiatives and capabilities	Prior and post-sales support	Tool tracking procedures	Preventative maintenance
Ethics	Subcontractor policies	Competitive pricing	Capability analysis
Management's commitment to the customer	Environmental programs	Policies and procedures	Percent of business partnership will represent
Housekeeping	Calibration history	Multiple plants	Geographical location

successful partnership are not being considered prior to asking the suppliers for substantial contributions, then the chances of a successful partnership will decrease. However, if the buyer is aware of the eight attributes, the buyer may be more willing to embrace a partnership-oriented relationship with the suppliers, and the chances for success in this area should improve.

Defining Terms

Supplier certification: Process used to identify those suppliers who the customer is assured will consistently provide materials and processes that conform to all expectations and requirements.

Just-in-time (JIT) purchasing: The process and product of merging buyer/supplier efforts to be responsive to each other's needs while conducting business in a way that provides maximum potential for growth and profit by both parties.

References

Deming, W. E. *Out of the Crisis*, MIT, Center for Advanced Engineering Study, Cambridge, MA, 1986.

Dobler, D. W., Lee, L., and Burt, D. N. *Purchasing and Materials Management: Text and Cases*, McGraw Hill, New York, 1990.

Ferrell, P. V. Purchasing into the '90s ... and beyond, *Purchasing World*, 34(1): 27–29, 1990.

Hahn, C. K., Pinto, P. A., and Bragg, D. J. 'Just-in-time' production and purchasing, *J. Purch. Mater. Mgt.*, 26(7): 2–10, 1983.

Hahn, C. K., Watts, C. A., and Kim, K. Y. The supplier development program: a conceptual model, *J. Purch. Mater. Mgt.*, 26(2): 2–7, 1990.

Ishikawa, K. *Guide to Quality Control, 2nd rev. ed.*, UNIPUB/Quality Resources, White Plains, NY, 1986.

Lee, S. M. and Ansari, A. Comparative analysis of Japanese just-in-time purchasing and traditional U.S. purchasing systems, *Int. J. Prod. Mgt.*, 5(4): 5–14, 1986.

McGaughey, N. W. Solving the technology puzzle, *Ind. Mgt.*, (July/August): 1989.

Schonberger, R. J. and Gilbert, J. P. Just-in-time purchasing: a challenge for U.S. industry. *Calif. Mgt. Rev.*, 26(1): 54–68, 1983.

For Further Information

An excellent source of information on purchasing in general, and JIT purchasing in particular, is the National Association of Purchasing Managers (NAPM). For information contact NAPM, P.O. Box 22160, Tempe, AZ 85285-2160, 800/888-6276 (http://www.napm.org.).

For nice summaries of the current state of JIT purchasing see Fawcett, S. E. and Birou, L. M. Just-in-time sourcing techniques: current state of adoption and performance benefits, *Prod. Inv. Mgt.*, first quarter, 1993; Goldhar, D. Y. and Stamm, C. L. Purchasing practices in manufacturing firms, *Prod. Inv. Mgt.*, third quarter, 1993.

13.8 Design, Modeling, and Prototyping

William L. Chapman and A. Terry Bahill

To create a product and the process that will be used to manufacture it, an engineer must follow a defined system design process. This process is an iterative one that requires refining the requirements, products, and processes of each successive design generation. These intermediate designs, before the final product is delivered, are called **models** or **prototypes**.

A model is an abstract representation of what the final system will be. As such, it can take on the form of a mathematical equation, such as $f = m \times a$. This is a deterministic model used to predict the expected force for a given mass and acceleration. This model only works for some systems and fails both at the atomic level, where quantum mechanics is used, and at the speed of light, where the theory of relativity is used. Models are developed and used within fixed boundaries.

Prototypes are physical implementations of the system design. They are not the final design, but are portions of the system built to validate a subset of the requirements. For example, the first version of a new car is created in a shop by technicians. This prototype can then be used to test for aerodynamic performance, fit, drivetrain performance, and so forth. Another example is airborne radar design. The prototype of the antenna, platform, and waveguide conforms closely to the final system; however, the prototype of the electronics needed to process the signal often comprises huge computers carried in the back of the test aircraft. Their packaging in no way reflects the final fit or form of the unit.

The System Design Process

The system design process consists of the following steps.

1. Specify the requirements provided by the customer and the producer.
2. Create alternative system design concepts that might satisfy these requirements.
3. Build, validate, and simulate a model of each system design concept.
4. Select the best concept by doing a trade-off analysis.
5. Update the customer requirements based on experience with the models.
6. Build and test a prototype of the system.
7. Update the customer requirements based on experience with the prototype.
8. Build and test a preproduction version of the system and validate the manufacturing processes.
9. Update the customer requirements based on experience with the preproduction analysis.
10. Build and test a production version of the system.
11. Deliver and support the product.

This can be depicted gradually on a spiral diagram as shown in Fig. 13.9.

The process always begins with defining and documenting the customer's needs. A useful tool for doing this is quality function deployment (QFD). QFD has been used by many Japanese and American corporations to document the voice of the customer. It consists of a chart called the "house of quality". On the left is listed what the customer wants. Across the top is how the product will be developed. These are often referred to as *quality characteristics.* The "whats" on the left are then related to the "hows" across the top, providing a means of determining which quality characteristics are the most important to the customer [Akao, 1990; Bahill and Chapman, 1993].

After the customer's needs are determined, the design goes through successive generations as the design cycle is repeated. The requirements are set, and a model or prototype is created. Each validation of a model or test of a prototype provides key information for refining the requirements.

For example, when designing and producing a new airborne missile, the initial task is to develop a model of the expected performance. Using this model, the systems engineers make initial estimates for the partition and allocation of system requirements. The next step is to build a demonstration unit of the most critical functions. This unit does not conform to the form and fit requirements but is used to

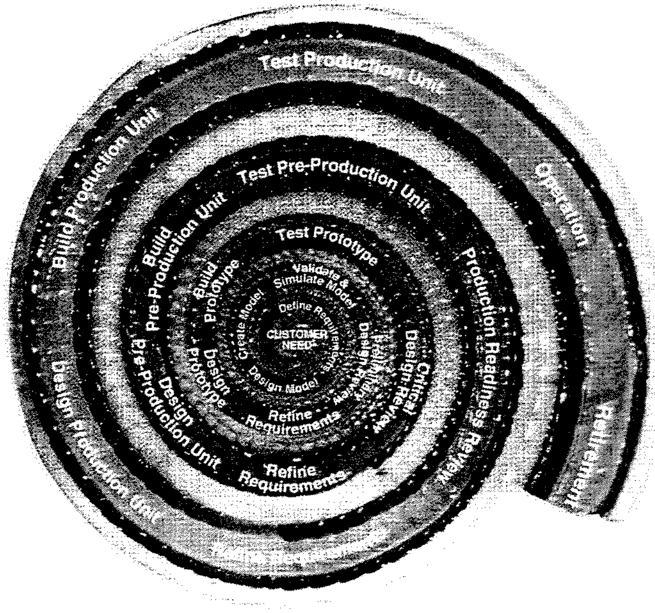


FIGURE 13.9 The system design process.

show that the system requirements are valid and that an actual missile can be produced. Requirements are again updated and modified, and the final partitioning is completed. The next version is called the *proof-of-design* missile. This is a fully functioning prototype. Its purpose is to demonstrate that the design is within specifications and meets all form, fit, and function requirements of the final product. This prototype is custom made and costs much more than the final production unit will cost. This unit is often built partly in the production factory and partly in the laboratory. Manufacturing capability is an issue and needs to be addressed before the design is complete. More changes are made and the manufacturing processes for full production are readied. The next version is the proof of manufacturing or the preproduction unit. This device will be a fully functioning missile. The goal is to prove the capability of the factory for full-rate production and to ensure that the manufacturing processes are efficient. If the factory cannot meet the quality or rate production requirements, more design changes are made before the drawings are released for full-rate production. Not only the designers but the entire design and production team must take responsibility for the design of the product and processes so that the customer's requirements are optimized [Chapman et al. 1992].

Most designs require a model upon which analysis can be done. The analysis should include a measure of all the characteristics the customer wants in the finished product. The concept selection will be based on the measurements done on the models. The models are created by first partitioning each conceptual design into functions. This decomposition often occurs at the same time that major physical components are selected. For example, when designing a new car, we could have mechanical or electronic ignition systems. These are two separate concepts. The top-level function — firing the spark plugs — is the same, but when the physical components are considered the functions break down differently. The firing of the spark plugs is directed by a microprocessor in one design and a camshaft in the other. Both perform the same function, but with different devices. Determining which is superior will be based on the requirements given by the customer, such as cost, performance, and reliability. These characteristics are measured based on the test criteria.

When the model is of exceptional quality a prototype can be skipped. The advances in computer-aided design (CAD) systems have made wire-wrapped prototype circuit boards obsolete. CAD models are so good at predicting the performance of the final device that no prototype is built. Simulation is repeated use of a model to predict the performance of a design. Any design can be modeled as a complex finite state machine. This is exactly what the CAD model of the circuit does. To truly validate the model, each state must be exercised. Selecting a minimum number of test scenarios that will maximize the number of states entered is the key to successful simulation. If the simulation is inexpensive, then multiple runs of this model should be done. The more iterations of the design process there are, the closer the final product will be to the customer's optimum requirements.

In the last two paragraphs, we mentioned functional decomposition and finite state machines as common design tools. There are many others and selection of the design tool is an important task [Bahill et al., 1998].

For systems where modeling works poorly, prototypes are better. Three-dimensional solids modeling CAD systems are a new development. Their ability to display the model is good, but their ability to manipulate and predict the results of fit, force, thermal stresses, and so forth is still weak. The CAD system has difficulty simulating the fit of multiple parts (such as a fender and car frame) because the complex surfaces are almost impossible to model mathematically. Therefore, fit is still a question that prototypes, rather than models, are best able to answer. A casting is usually used to verify that mechanical system requirements are met.

Computer-aided manufacturing (CAM) systems use the CAD database to create the tools needed for the manufacture of the product. Numerical control (NC) machine instructions can be simulated using these systems. Before a prototype is built, the system can be used to simulate the layout of the parts, the movement of the cutting tool, and the cut of the bar stock on a milling machine. This saves costly material and machine expenses.

Virtual reality models are the ultimate in modeling. Here the human is put into the loop to guide the model's progress. Aircraft simulators are the most common type of this product. Another example was demonstrated when the astronauts had to use the space shuttle to fix the mirrors on the Hubble telescope. The designers created a model to ensure that the new parts would properly fit with the existing design. They then manipulated the model interactively to try various repair techniques. The designers were able to verify fit with this model and catch several design errors early in the process. After this, the entire system was built into a prototype and the repair rehearsed in a water tank [Hancock, 1993].

Computer systems have also proved to be poor simulators of chemical processes. Most factories rely on design-of-experiments (DOE) techniques, rather than a mathematical model, to optimize chemical processes. DOE provides a means of selecting the best combination of possible parameters to alter when building the prototypes. Various chemical processes are used to create the prototypes that are then tested. The mathematical techniques of DOE are used to select the best parameters based on measurements of the prototypes. Models are used to hypothesize possible parameter settings, but the prototypes are necessary to optimize the process [Taguchi, 1976].

The progressive push is to replace prototypes with models because an accurate fully developed model is inexpensively simulated on a computer compared to the cost and time of developing a prototype. A classic example is the development of manned rockets. Figure 13.10 shows the number of test flights before manned use of the rockets.

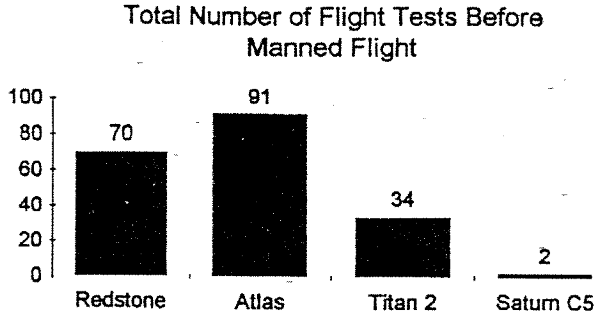


FIGURE 13.10 Flight tests for the manned space program rockets.

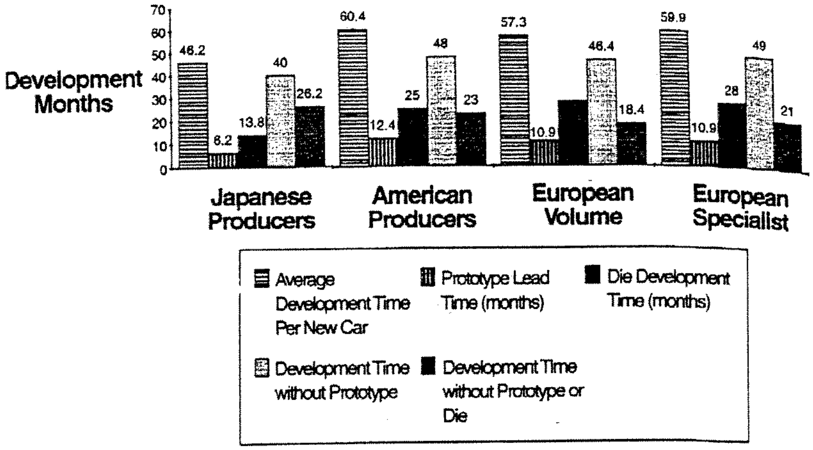


FIGURE 13.11 Comparison of Japanese, American, and European car producers. (*Source:* Womack, J. P., Jones, D. T., and Roos, D. *The Machine that Changed the World*, Rawson Associates, New York, 1990.)

The necessity for prototypes diminished rapidly as confidence in computer models developed. Initially, many of the rockets exploded in their first attempts at launch. As more was learned about rocketry, sophisticated models were developed that predicted performance of the rocket based on real-time measurements of valves, temperatures, fuel levels, and so forth. Using modern computers, the entire model could be evaluated in seconds and a launch decision made. This eliminated the need for many flight tests and reduced the cost of the entire Apollo moon-landing program.

Rapid Prototyping

Rapid prototyping is the key to reducing design time for parts and processes. Design is an iterative process. By creating prototypes quickly, the design can be completed faster. Japanese automobile manufacturers develop prototypes of their products in 6 months, whereas American companies take 13 months [Womack et al., 1990]. This advantage allows the Japanese companies to get to the market faster, or if they choose they can iterate their design one more time to improve their design's conformance to the customer's requirements. Japanese automakers' ability to create the prototype quickly is due in part to better coordination with their suppliers but also to the exacting use of design models to ensure that the design is producible.

As seen in Fig. 13.11, the lead in prototype development accounts for 44% of the advantage the Japanese producers have in product development time. The rest of the advantage if from rapid creation of the huge dies needed to stamp out the metal forms of the automobiles. The design of these important manufacturing tools is given as much attention as the final product. By creating flexible designs and ensuring that the teams that will produce the dies are involved in the design process, the die development time is cut from 25 months in the United States to 13.8 months in Japan. The rapid creation of the tooling is a key to fast market response.

Stereolithography is a new method of creating simple prototype castings. The stereolithography system creates a prototype by extracting the geometric coordinates from a CAD system and creating a plastic prototype. The solids model in the CAD system is extracted by "slicing" each layer in the z-axis into a plane. Each layer is imaged by a laser into a bath of liquid photopolymer resin that polymerizes with the energy from the laser. Each plane is added, one on top of the other, to build up the prototype. The final part is cured and polished to give a plastic representation of the solids model. It illustrates the exact shape of the part in the CAD system. This technique will not, however, verify the function of the final product because the plastic material used will not meet strength or thermal requirements [Jacobs, 1992].

Software developers also use rapid prototyping. This technique is used to get a fast though barely functional version of the product into the customer's hands early in the design cycle. The prototype is created using the easiest method to simulate functionality to the viewer. The customer comments on what is seen and the developers modify their design requirements. For example, when developing expert systems, models are almost never used. One of the driving rules is to show a prototype to the customer as soon as possible and afterwards throw it away! The purpose of building the prototype was to find out what the knowledge that needs to be represented is like so that the appropriate tool can be selected to build the product. If, as is usually the case, a nonoptimal tool was used for the prototype, then the prototype is thrown away and a new one is developed using better tools and based on better understanding of the customer's requirements. Beware, though — often a key function displayed in the prototype is forgotten when the prototype is abandoned. Be certain to get all the information from the prototype [Maude and Willis, 1991]. The fault with this technique is that the requirements are not written down in detail. They are incorporated into the code as the code is written, and they can be overlooked or omitted when transferred to a new system [Bahill et al., 1995].

When to Use Modeling and Prototyping

When should modeling vs. prototyping be used? The key difference is the value of the information obtained. Ultimately, the final product must be created. The prototype or model is used strictly to improve the final product. Costs associated with the prototype or model will be amortized over the number of units built. The major problem with models is the lack of confidence in the results. Sophisticated models are too complex for any single engineer to analyze. In fact, most models are now sold as proprietary software packages. The actual algorithms, precision, and number of iterations are rarely provided. The only way to validate the algorithm (not the model) is by repeated use and comparison to actual prototypes. It is easier to have confidence in prototypes. Actual parts can be measured and tested repeatedly, and the components and processes can be examined. Prototypes are used more often than models once the complexity of the device exceeds the ability of the computer to accurately reflect the part or process. During the initial design phases, models must be used because a prototype is meaningless until a concept has been more firmly defined. At the other extreme, modeling is of limited benefit to the factory until the configuration of the part is well known. A general rule is to build a model, then a prototype, then a production unit. Create even a simple mathematical model if possible so that the physics can be better understood. If the prototype is to be skipped, confidence in the model must be extremely high. If there is little confidence in the model, then a minimum of two or three prototype iterations will have to be done.

Defining Terms

Model: An abstract representation of what the final system will be. It is often a mathematical or simplified representation of a product.

Prototype: A physical representation of a product built to verify a subset of the system's requirements.

Stereolithography: A prototype-manufacturing technique used to rapidly produce three-dimensional polymer models of parts using a CAD database.

References

Akao, Y., Ed., *Quality Function Deployment: Integrating Customer Requirements into Product Design,* Productivity Press, Cambridge, MA, 1990.

Bahill, A. T. and Chapman, W. L., A tutorial on quality function deployment, *Eng. Mgt. J.,* 5(3): 24–35, 1993.

Bahill, A. T., Bharathan, K., and Curlee, R. F., How the testing techniques for a decision support system changed over nine years, *IEEE Trans. Systems, Man and Cybernetics,* 25: 1533–1542, 1995.

Bahill, A. T., Alford, M., Bharathan, K., Clymer, J., Dean, D. L., Duke, J., Hill, G., LaBudde, E., Taipale, E., and Wymore, A. W., The design-methods comparison project, *IEEE Trans. Systems, Man and Cybernetics,* Part C: Applications and Reviews, 28(1): 80–103, 1998. Simulations used in this project are available at http://www.sie.arizona.edu/sysengr/methods.

Chapman, W. L., Bahill, A. T., and Wymore, A. W., *Engineering Modeling and Design*, CRC Press, Boca Raton, FL, 1992.
Hancock, D., Prototyping the Hubble fix, *IEEE Spectrum*, 30(10): 34–39, 1993.
Jacobs, P. F., *Rapid Prototyping & Manufacturing: Fundamentals of StereoLithography*, McGraw-Hill, New York, 1992.
Maude, T. and Willis, G., *Rapid Prototyping: The Management of Software Risk*, Pitman, London, 1991.
Taguchi, G. *Experimental Designs, 3rd ed., vols. 1 and 2*, Maruzen, Tokyo, 1976.
Womack, J. P., Jones, D. T., and Roos, D. *The Machine that Changed the World*, Rawson Associates, New York, 1990.

Further Information

Pugh, S. *Total Design: Integrated Methods for Successful Product Engineering*, Addison-Wesley, London, 1990.
Suh, N. P. *The Principles of Design*, Oxford University Press, New York, 1990.
Wymore, A. W., *Model-Based Systems Engineering*, CRC Press, Boca Raton, FL, 1993.

13.9 Flexible Manufacturing

Layek Abdel-Malek and Lucio Zavanella

The birth of the global village poses a myriad of problems and challenges to manufacturers all over the world. Today's decerning consumers demand, in addition to customization and affordable prices, high-quality products as well as delivery in short lead times. As a result, *flexible manufacturing* has emerged as a strategic imperative for industry in order to succeed in the current competitive environment.

Many experts agree that the 20th century has witnessed the evolution of three inclusive strategic imperatives in manufacturing. The first one resulted from Fredrick Taylor, who had set forth the principles of scientific management [Taylor, 1911]. The implementation of its main principle, efficiency, in Ford's Motor company in 1913 led to a remarkable success. Soon after Ford's growth, many companies had focused on improving the efficiency of their plants. Later, in the 1950s, quality had become the second strategic imperative of the era. The consumers of that time had not only cared about low prices that resulted from high efficiency but they also valued the quality and the reliability of their goods.

In addition to efficiency and quality, and facilitated by advances in automation and computer technologies, **flexibility** and flexible manufacturing have lately emerged as the essential strategic imperative of the 1990s for manufacturers' viability.

Our taxonomy in this section is as follows: after this introduction, we define flexibility and its classes, present a historical background and definition of the current flexible manufacturing systems and their components, introduce the concept of telemanufacturing as a flexible paradigm, and conclude with a section for references and further readings.

Flexibility

Despite its importance in manufacturing environment and the numerous writings in this subject matter, flexibility means different things to different people. One of the widely accepted definitions of flexibility is the ability of the manufacturer to fulfill customers' demands in a timely fashion. The deliverables are expected to be customized products that enjoy high quality at affordable prices. Nevertheless, despite differences in its definition, praticioners and academicians seem to agree on flexibility major classes (attributes). Table 13.10 lists these classes and their brief descriptions. Of these listed flexibility classes, however, manufacturers appear to value more those of product mix, volume, process, and routing. It should be pointed out, though, that these flexibility classes are not necessarily independent of each other.

Evaluating a manufacturing system's flexibility is important for gauging a company's standing with respect to its competitors. Several methods and indices have been developed to measure flexibility and its attributes. The interested reader is referred to Abdel Malek et al. [1996], Benjaffar and Ramamrishnan

TABLE 13.10 Flexibility Classes

Flexibility Class	The ability to
Expansion	Add or reduce capacity easily and modularly
Machine	Change tools and fixtures to process a given part set
Mix	Absorb changes in product mix
Mix-change	Alter manufacturing processes to accomodate new part types
Volume	Operate economically at different output levels
Process	Interchange the ordering of operations for a given part type
Routing	Process a given part set on alternative machines
Programming	Alter basic operating parameters via control instructions
Communications	Transmit and receive information or instructions

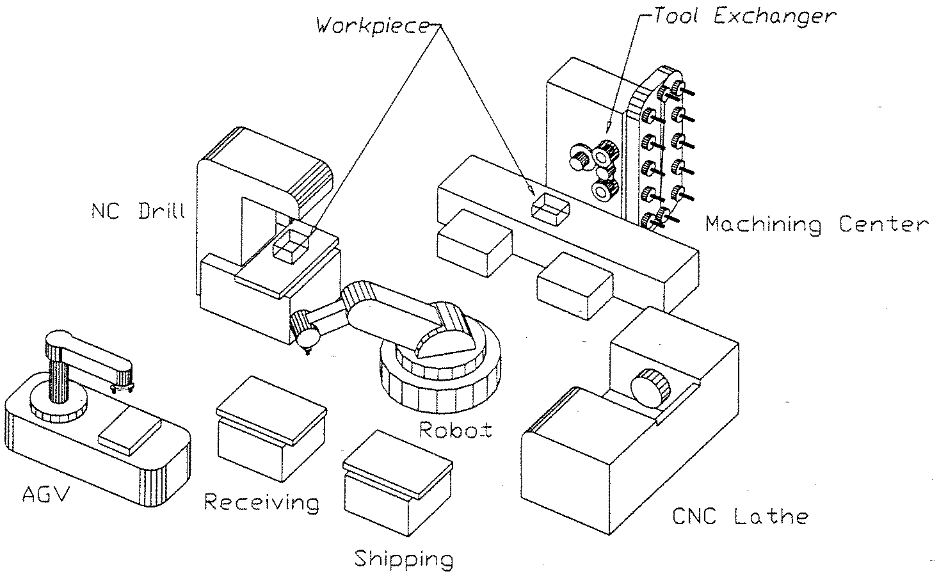


FIGURE 13.12 Example of a FMS.

[1996], Brill and Mandelbaum [1989], and Das [1996] for some of these measures. Also, further readings are provided in the reviews by Sethi and Sethi [1990] and Sarker et al. [1994].

The aforementioned discussion of flexibility and its classes is mainly pertinent to technology, where most of the published works have focused. However, it is equally important in attaining the agility of a manufacturing enterprise to have flexibility in its infrastructure as well as its labor force [Slack, 1987].

Flexible Manufacturing Systems

It is believed that the first **flexible manufacturing system** (FMS), as it is known today, was designed in the early 1960s by Williamson and developed in 1965 by Sunstrand Corp. FMSs were conceived as a result of the ability to program the path of a cutting tool on a punched tape, introducing the concept of numerical control (NC). The off-line programmability of NC machine tools presented a significant evolution because of the ease of change between setups of different production runs. (This evolution in the concept of controlling machine tools was in contrast to that of the hard automation of manufacturing systems, which prevailed at that time, known as transfer lines. A transfer line consists of a set of special-purpose machines arranged in tandem, each carrying out single or multiple tasks. In a transfer line, the change between products requires a substantial effort and time because of the need to physically replace gadgets.)

Before defining the various types of FMSs, hereafter is a description of their most common components and subsystems (see also Fig. 13.12).

NC Machine

Developed at MIT in 1952, it is a machine tool guided by instructions that are punched on a tape and decoded by a reader interfaced with the tool positioning system.

Direct Numerical Control (DNC) of Machines

in the 1960s, technological advances in electronics allowed the control of several NC machines by one computer (or a hierarchy of them). This control system, referred to as DNC, stores in the central computer a database for the production cycles of the machines and monitors the plant's conditions. (Because of problems such as voltage fluctuations and possibility of fault of the mainframe computer, the use of this type of control system started to decline in the succeeding decade.)

CNC Machine (Computerized NC)

In the 1970s, the NC machine control was successfully implemented on an on-board computer. Because of the development of the powerful microcomputer, this controlling unit also attended to various machining functions (such as feed, depth of cut, etc.) and to tool paths, allowing the machine to perform various supervised trajectories around several axes at the same time.

Machining Center

It is an NC or CNC machine tool that is capable of executing different operations, such as drilling, boring, milling, etc. on different surfaces of the work piece. Several tools are arranged on a magazine. The machining center is usually equipped by an automatic tool and a workpiece exchanger.

Robot

Developed in the late 1950s, it is a reprogrammable multifunction manipulator that can perform a variety of tasks, such as material handling, welding, painting, drilling, machine loading and unloading, etc. Some of its most important characteristics are degrees of freedom, type of control (point-to-point, continuous path), payload, reach (envelope volume), repeatability, and accuracy. The type of use of the robot determines the importance of these characteristics.

Automated Guided Vehicles (AGVs)

Developed in the mid-1950s, they are computer-controlled carts for transporting jobs between stations on the factory floor. Their ability to select and alter routes and paths makes them suitable for transportation in a flexible environment. AGVs can be guided by wires or radio signals or optically by infrared sensors. These programmable transporters link different stations under computer control. Some AGVs are equipped with a robot arm.

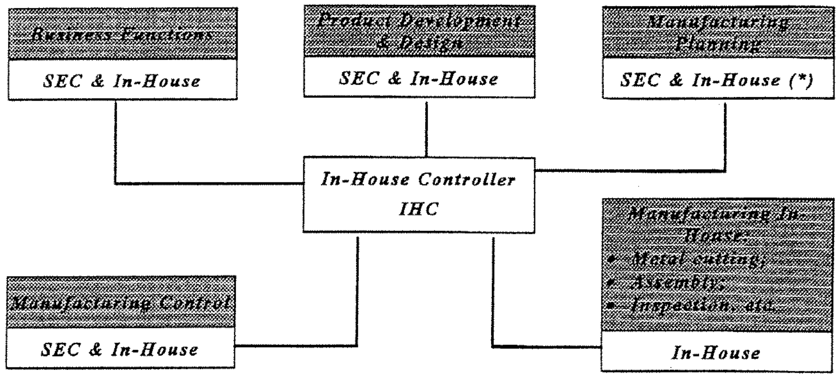
Automated Storage/Retrieval System (AS/RS)

Its development is linked to that of minicomputer in the late 1960s. An AS/RS consists of several subsystems that operate under a central control system. Two of their most common types are the rack/container system and the carousel/bin system. In the first type, each of the items is stored in a set of containers or, alternatively, on pallets that are arranged in aisles and served by a shuttle. The shuttle automatically moves between aisles to bring or to pick up from the loading/unloading point the needed items. The other type is the carousel system. Usually, it is used for small and light products. Items are located in specified bins, and the whole carousel automatically rotates so that the needed bin is properly alligned in the proximity of the loading/unloading point to deliver or receive.

Different arrangements and combinations of the aforementioned resources result in various types of FMSs. Browne et al. [1984] categorize these systems into four types:

Type I, flexible machining cell, is a single CNC machine that interacts with material handling and storage systems.

Type II, flexible machining system, is a group of machining stations linked by a material handling system and connected by a flexible transport system. Part production and material flow are controlled on-line. Routes and scheduling are also controlled and adjusted according to the system's conditions.



(*) SEC & In-House: acitivity could be performed In-House and/or by a SEC

FIGURE 13.13 The telemanufacturing enterprise.

Type III, flexible transfer lines, is a set of machines and workstations in tandem where each performs one operation under the control of a computer.

Type IV, flexible transfer multi-line, is the multiple case of the preceding category, where the various single flexible transfer lines are interconnected.

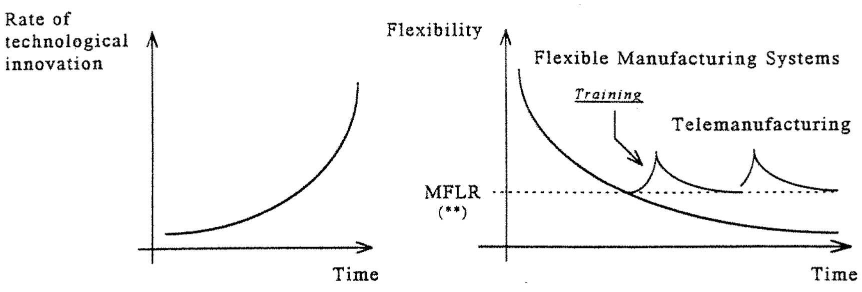
These types of systems have short setup times (due to the ability of off-line reprogramming and preprogramming). This in turns allows the production of smaller batch sizes and large varieties of product mix. Additionally, these systems offer capabilities for various processing sequences and machining alternatives of parts as well as the ability of producing a particular item via multiple routes. These characteristics, as mentioned before, are essential attributes of flexibility. Also, another positive characteristic of these systems is the reduction of the amount of work in process. Nevertheless, these systems, especially type II, require a large investment to acquire, and their flexibility is bound by the available technology and budget at the time of installation. Moreover, the flexibility depends on the system designers' ability to forecast the types and specifications of products that would be manufactured in the future. If market conditions change from what was anticipated at the time of the design, and quite often they do, the system acquired could suffer from lack of the needed flexibility. Upton [1995] reports incidences and difficulties that were encountered where industries suffered because of the limitation of these FMSs.

The leap in the information and computer technologies experienced in the mid-1990s is credited for the renewed emphasize on flexible manufacturing and change in notion, that is, to achieve flexible manufacturing, it is no longer necessary to have a highly automated environment on the factory floor (as was the original notion in the early 1960s). The following section describes an emerging concept in flexible manufacturing, which has been coined **telemanufacturing**.

Telemanufacturing

The premise of telemanufacturing is flexibility, adaptability, and affordability. The term telemanufacturing coins an infrastructure whereby a company can outsource several of its production and design functions, particularly via information superhighways, rendering in real-time activities essential for production of goods [Abdel Malek et al., 1996].

As will be discussed later, this kind of structure avoids problems that are inherent in the types of FMSs described before. Fig. 13.13 shows a schematic diagram for a telemanufacturing enterprise. In addition to communication media (both internal and external), the telemanufacturing enterprise requires two essential types of components: the in-house controller (IHC) and the other component is a set of service providers such as houses specialized in design, production control, or customer billing. We designate these houses as specialized expert centers (SECs). The following is a brief description.



(**) MFLR: Minimum Flexibility Level Requirement to stay competitive

Technological Innovation *Flexibility trend*

FIGURE 13.14 Telemanufacturing and flexibility level.

Specialized Expert Centers (SECs)

It is a center that possesses the state of the art in a certain field with various facets, whether it is software or hardware. Its human resources are well trained, enjoying advanced expertise in the respective fields, and have access to the latest pertinent information and development. Examples of the expert centers could be those research centers that currently exist in universities as well as those of EDS (electronic data systems). Today, many companies employ the latter type for their billing and payroll. To illustrate the former, consider university research centers that may be specialized in digital design or composite material; they can render their expertise to manufacturers that seek them. This provide the manufacturers with the option to select the center they wish to subscribe to. Also, manufacturers could choose the functions that they wish to perform themselves or outsource to SECs, according to their prevailing conditions and needs, consequently enhancing flexibility.

In-House Controller (IHC)

It is an essential control component that integrates the expert centers, manufacturing floor activities, and the other functions. Then it orchestrates the execution process according to predetermined protocols. The IHC consists of an in-house team and computers that have the necessary databases, software, and modules that interactively communicate with the different SECs and the manufacturing functions on the floor. It harmonizes the different decisions, and centralizes the final one, preceding execution. In essence, the IHC is the brain of the telemanufacturing enterprise.

Communication Media

There are two media necessary for the telemanufacturing enterprise: One for within the enterprise connections and the other for outside communication. The inside communication could be carried out using one of those commercially available for computer integrated manufacturing (CIM), such as local area network (LAN) or wide area network (WAN). Its basic function is to communicate between the IHC and the factory floor as well as between workstations.

As for the external media, the Internet could provide the enterprise with means to the outside connection, mainly to communicate between the IHC and the different SECs, or, depending on the frequency of usage, especially dedicated lines could be setup for the interaction.

The Logic of Telemanufacturing and its Relation to Flexibility Reenforcing

Telemanufacturing allows a company to remain flexible throughout. Since it permits a company to cosource some of its production functions to expert centers, consequently, as shown in Fig. 13.14, the flexibility level of the telemanufacturing enterprise is not dependent on the technological obsolescence of its systems' components. Its flexibility is mostly dependent on that of the SECs subscribed to. It is reasonable to assume

TABLE 13.11 A Comparison of Modern Manufacturing Concepts

	CIM Technology	Holonic Manufacturing	Telemanufacturing
Flexibility	Restricted by equipment	Restricted by equipment	Limited by state of the art
Adaptability	Workforce dependent	Workforce dependent	Semidependent on workforce
Investment	People, hardware, software	People, hardware, software	Subscription and low cost of software and hardware

that, in order for these SECs to survive, they must keep adopting new technologies; otherwise, subscribers can change to other service providers. Therefore, it can be conjuctured that applying telemanufacturing sustains and reenforces flexibility of the enterprise. (Similar structures have been utilized with remarkable success. We cite the system developed by SAP and used in Boeing's aircraft programs.)

Additionally, it is plausible to assume that, because of technological innovation, a software or a machine that is very sophisticated (top of the line) today may not be the same tomorrow. Hence, if the company buys the equipment or the software, it will risk (depending on the equipment) its future obsolescence. Meanwhile, if it can use a SEC, in addition to avoiding training costs, initial investment, and time for acquisition, the problem of obsolescence will be that of the SEC (which has to maintain the upgrading of its equipment for survival). Table 13.11 provides a comparison between telemanufacturing and the various recent manufacturing structures vis a vis their flexibility, adaptability, and investment.

Acknowledgments

The first author appreciates the partial support provided by National Science Foundation (NSF) grant #DMI9525745 and the Italian Council of National Research (CNR).

Defining Terms

Flexibility: The ability of a manufacturer to efficiently respond to the volatile market needs in a timely fashion, delivering high-quality products at competitive prices.

Flexible manufacturing systems (FMS): A set of reprogrammable machinery, automated material handling, storage and retrieval devices, and a host computer. This computer controls the various activities of the system.

Telemanufacturing: The infrastructure whereby a company can outsource several of its production and design functions, particularly via information superhighways, rendering in real-time activities essential for production of goods.

References

Abdel Malek, L., Wolf, C., and Guyot, P. Telemanufacturing: A Flexible Manufacturing Solution. *Preprints of 9th Int. Working Seminar on Production Economic,* on *Int. J. Prod. Econ.*, 3: 347–365, 1996.

Benjaffar, S. and Ramamrishnan, R. Modelling, measurement and evaluation of sequencing flexibility in manufacturing systems, *Int. J. Prod. Res.*, 34(5): 1195–1220, 1996.

Brill, P. H. and Mandelbaum, M. On measures of flexibility in machining systems, *Int. J. Prod. Res.*, 27(5): 5–23, 1989.

Browne, J., Dubois, D., Rathmill, K., Sethi, S., and Stecke, K. Classification of flexible manufacturing systems, *FMS,* 114–117, 1984.

Das, S. The measurement of flexibility in manufacturing systems, *Int. J. Flex. Manuf. Syst.*, 8: 67–93, 1996.

Sarker, B., Krshnamurthy, S., and Kuthethur, S. A survey and critical review of flexibility measures in manufacturing systems, *Int. J. Prod. Plan. Control*, 5(6): 512–523, 1994.

Sethi, A. K. and Sethi, S. P. Flexibility in manufacturing: a survey, *Int. J. Flex. Manuf. Syst.*, 2: 289–328, 1990.

Slack, N. The flexibility of manufacturing systems, *Int. J. Prod. Mgt.*, 1(4): 35–45, 1987.

Taylor, F. W. *Principles of Scientific Management,* Harper and Row, New York, 1911.

Upton, D. What really makes factories flexible?, *Harv. Bus. Rev.*, July-August: 74–84, 1995.

Further Information

Asfhal, C. R. *Robots and Manufacturing Automation*, John Wiley & Sons, New York, 1985.

Chang, T. C., Wang, H. P., and Wysk, R. *Computer-Aided Manufacturing*, Prentice Hall, Englewood Cliffs, NJ, 1991.

Groover, M. *Fundamentals of Modern Manufacturing Materials, Processes, and Systems.* Prentice Hall, Englewood Cliffs, NJ, 1996.

Gupta, D. and Buzacott, J. A. A framework for understanding flexibility of manufacturing systems, *J. Manuf. Syst.*, 8(2): 89–96, 1989.

Hitomi, K. *Manufacturing Systems Engineering*, Taylor & Francis, 1979.

Miller, R. K. *Automated Guided Vehicles and Automated Manufacturing*, SME, 1987.

Jamshidi, M., Lumia, R., Mullins, J., and Shahinpoor, M. *Robotics and Manufacturing: Recent Trends in Research, Education and Applications*, ASME Press, New York, 1992.

Kusiak, A. *Intelligent Manufacturing Systems*, Prentice Hall, Englewood Cliffs, NJ, 1990.

McAfee, A. and Upton, D. The real virtual factory, *Harv. Bus. Rev.*, July-August: 123–135, 1996.

Tompkins, J. A. and Smith, J. D. *The Warehouse Management Handbook*, McGraw-Hill, New York, 1988.

13.10 Design for Manufacturability

Xiaoping Yang and C. Richard Liu

In the launching of a new product, lead time, quality, and cost are the key factors that determine the competitiveness of the product. Consequently, shortening lead time, improving quality, and reducing cost are of paramount importance for any company to survive and excel. The significance of product manufacturability in achieving the forgoing goals has long been recognized and intensive efforts have been taken to improve product manufacturability. All the methods preceded **design for manufacturability (DFM)** such as **value analysis (VA)**, however, are *serial* in nature and do not enter consideration until the product design is completed. As a result, they incur high cost of design change (see Fig. 13.15). Moreover, they are not very thorough and cannot offset the poor decisions made during the early design stages. It has been recognized that design is the first step in product manufacture. Design decisions have greater influence on the cost of manufacturing than manufacturing decisions. Therefore, manufacturing issues should be considered as early as possible so as to make the right decisions the *first time.*

DFM is the practice that brings the consideration of manufacturing issues into early stages of product design process to insure that all issues are considered *concurrently* so that the product can be made in the least time with the desired level of quality and the least cost. DFM is no longer optional but *a must* for any company to be successful in today's competitive global market. DFM plays an important role in **computer-integrated manufacturing** and is an important tool for accomplishing **concurrent engineering (CE)**. It involves such procedures as ascertaining the customer's real needs, design for function, materials and processes selection, design for assembly (DFA), design for processes, design for reparability and maintainability, design for safety, and design for disposal and recycle.

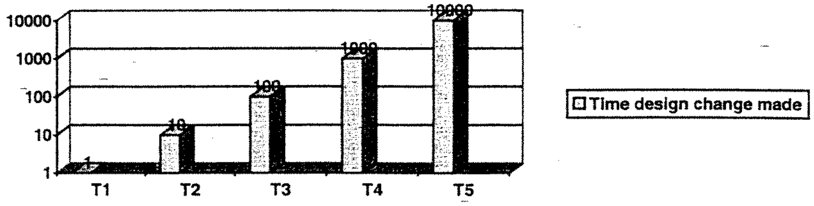


FIGURE 13.15 Comparative cost of an engineering change in different stages in the product cycle. T1: during design, T2: design testing, T3: process planning, T4: pilot production, and T5: final production. (*Source:* Shina, S. G. *Concurrent Engineering and Design for Manufacture of Electronics Products*, Van Nostrand Reinhold, New York, 1991.)

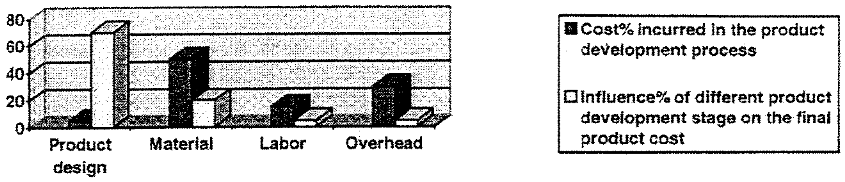


FIGURE 13.16 The product design has the greatest impact. (*Source:* Boothroyd, G. et al. *Product Design for Manufacture and Assembly,* Marcel Dekker, New York, 1994.)

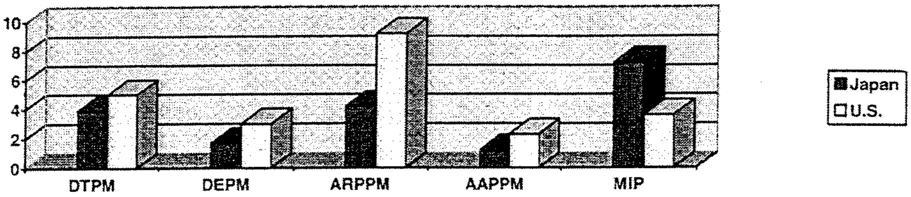


FIGURE 13.17 Comparison between Japanese and U.S. auto industry. DTPM: design time/model (years), DEPM: design effort/model (man hours), ARPPM: average replacement period/model (years), AAPPM: average annual production/model (×100,000), and MIP: models in production (×10). (*Source:* Shina, S. G. *Concurrent Engineering and Design for Manufacture of Electronics Products,* Van Nostrand Reinhold, New York, 1991.)

Why DFM and What Are the Benefits of Applying DFM?

Fragmenting a product design into subtasks in the traditional approach often leads to *conflicting decisions* made by different departments that are responsible only for their own duties and suboptimal design. Consequently, the product development cycle is long because iterations are needed to resolve decision conflicts between different departments, the quality is low, and the cost is high. In today's competitive world market, the company practicing the serial product design process finds itself losing profits and market share. It may even be wiped out the market. Therefore, DFM is *indispensable* for a company to survive and excel because, by transforming the *serial* process into a *parallel* one that facilitates the early resolving of conflicts among different departments and making decisions leading to the global optimization of the product design, DFM can shorten lead time, improve quality, and reduce cost.

It is emphasized that the DFM be considered in the early *conceptual design* stage to get the maximized benefits because 70% of the final product cost has been committed in product design. The later the engineering change, the higher the cost. Refer to Figs. 13.15 and 13.16. Figure 13.17 illustrates the main advantage of DFM. Detailed discussion is in Shina [1991].

DFM Guidelines

1. Design starts from ascertaining the *real* customer needs. It is important that the ascertained needs are real because unreal needs lead to increased complexity of the product and consequently result in increased manufacturing cost, decreased system reliability, and increased repair and maintenance cost. [Trappey and Liu, 1992].
2. Starting from the ascertained needs, the typical hierarchical structure of design includes conceptual design, configuration design, and parametric design. The design proceeds from one level to another in the hierarchy until the design is finished. In each level, design alternatives are generated and evaluated to find the best design candidate from the *global* point of view before it moves on to the next stage. See[Trappey and Liu [1992] for more information.
3. The best design is the *simplest* design that satisfies the needs. Design for function that aims at satisfying the minimum required function in the most effective manner can lead to simplified

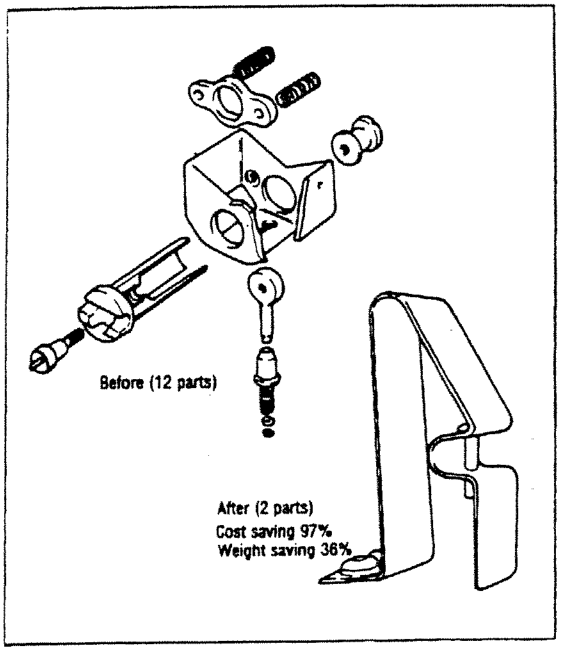


FIGURE 13.18 Improved design of a locking mechanism by design for function. (*Source:* Jacobs, G. *Engineering,* February: 178–182, 1980.)

designs, the benefits of which are lower cost and improved quality and reliability. See Fig. 13.18 for an example.

4. It is emphasized that the interaction between materials and processes be considered in materials and processes selection because only certain combinations of manufacturing processes and materials are possible. The general considerations of materials selection are properties, cost, and availability. The general considerations for selecting manufacturing processes are materials, dimensional and surface finish, operational and manufacturing cost, and production volume. The selection process ends up with a compatible combination of materials and processes. When more than one materials/processes combination satisfies design requirements, all alternatives are ranked according to various criteria and the best selected. Boothroyd et al. [1994] summarize compatibility between processes and materials and shape generation capabilities of processes with DFA compatibility attributes. Cost factors for process selection are materials, direct labor, indirect labor (setup, etc.), special tooling, perishable tools and supplies, utility, invested capital, etc. Every effort should be made to minimize the *total* unit cost in the selection process. The setup cost and special tooling cost are production-volume dependent. For a product of low volume, the number of operations should be kept minimum because the setup cost accounts for a large percentage of the total product cost. See Bralla [1986] and Liu and Mittal [1996]. Tolerance plays an important role in product cost. The tighter the tolerance and surface finish, the higher the cost. Refer to Figs. 13.19 and 13.20.
5. The goal of DFA is to ease the assembly of the product. Boothroyd et al. propose a method for DFA that involves two principal steps:
   - Designing with as few number of parts as possible. This is accomplished by analyzing parts pair-wise to determine if the two parts can be created as a single piece rather than as an assembly.
   - Estimating the costs of handling and assembling each part using the appropriate assembly process to generate costs figures to analyze the cost savings through DFA.
   - In addition to the assembly cost reductions through DFA, there are reductions in part costs that are often more significant. Other benefits of DFA includes improved reliability and reduction

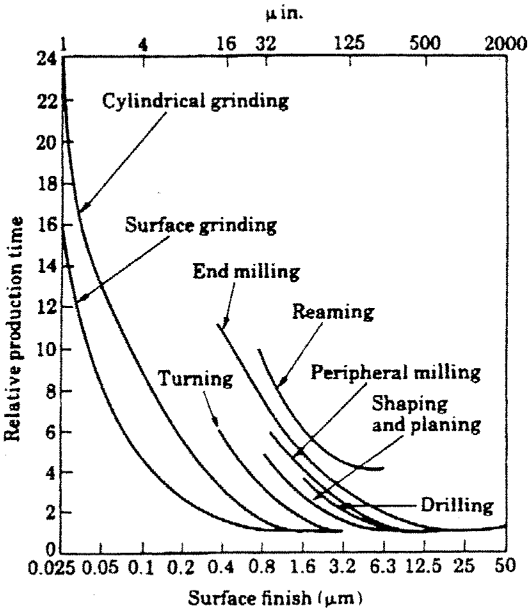


FIGURE 13.19 Relative production time as a function of surface finish produced by various manufacturing methods. (*Source:* Kalpakijian, S. *Manufacturing Processes for Engineering Materials, 3rd ed.*, Addison-Wesley, Menlo Park, CA, 1996.)

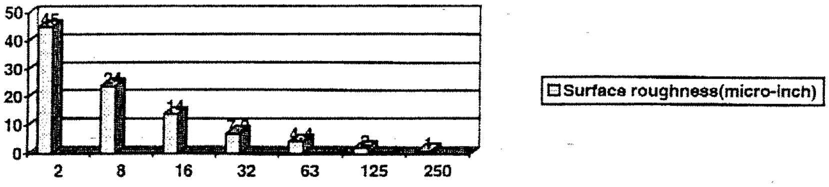


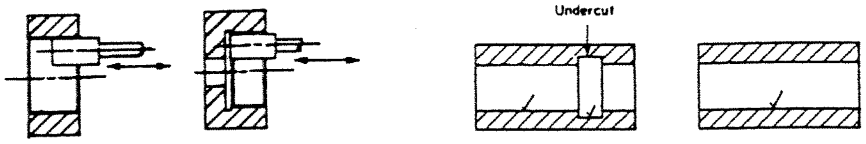
FIGURE 13.20 Relative cost corresponding to different surface roughness. (*Source:* Bralla, J. G. *Handbook of Product Design for Manufacturing,* McGraw-Hill, New York, 1986.)

in inventory and production control costs. Consequently, DFA should be applied regardless of the assembly cost and production volume. See Boothroyd et al. [1994] for more information.

6. Design for processes:

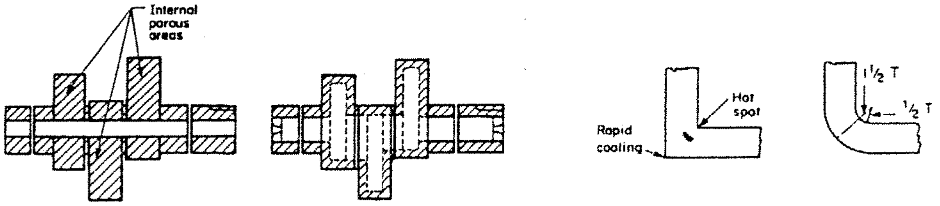
Design for machining: Machining is almost always needed if precision is required. The great flexibility is another advantage of machining, and it is particularly economical for products of low volumes. As there are always some materials wasted in machining, it becomes less favorable as the product volume increases. Avoid machining processes whenever possible. If machining has to be involved, then make every effort to minimize the materials wasted. Do not use tight dimensional tolerances and surface finish unless required by product function. Avoid expensive secondary operations such as grinding, reaming, and lapping if possible. Avoid features that need special cutters. Make sure that the features to be machined are accessible (see Fig. 13.21A). Design parts such that the number of machining operations are minimal (see Fig. 13.21B). Refer to Boothroyd et al. [1994] and Bralla [1986].

Design for metal forming: A major advantage of metal forming over machining is that there is little or no material waste in the processes. Materials savings become more significant as the raw materials become higher priced. However, the special tooling is usually a significant



Good Designs Bad Design Good Design

FIGURE 13.21 Examples of good designs and bad designs for machining. (A) Internal grinding: make sure the feature to be machined is accessible. (*Source:* Boothroyd, G. et al. *Product Design for Manufacture and Assembly,* Marcel Dekker, New York, 1994.) (B) Compare the bad design with undercut and the good design without undercut. (*Source:* Bralla, J. G. *Handbook of Product Design for Manufacturing,* McGraw-Hill, New York, 1986.)



Bad Design Good Design Bad Design Good Design

FIGURE 13.22 Examples of good designs and bad designs for casting. (A) Using uniform cross sections. (B) Rounding corners to avoid the hot spot. (*Source:* Bralla, J. G. *Handbook of Product Design for Manufacturing,* McGraw-Hill, New York, 1986.)

investment that can only be justified by a large volume of production. Because the materials flow plastically in the solid state, irregularities and intricate shapes should be limited in design and sharp corners avoided. Metal extrusion is particularly advantageous in producing long part with constant intricate cross-section. Because its relative low cost of tooling and its capability to incorporate irregular cross-sectional shapes in the extrusion dies such that machining could be eliminated, it could be justified for short runs. Avoid thin-walled extrusion and balance sections walls for extrusion. Stamping is only suitable for high-volume-production. Minimize bend stages and maximize stock utilization for stamping. A special benefit of forging process is that the grain structure can be controlled so as to improve physical properties of the metal. Aligning the parting line in one plane perpendicular to the axis of die motion if possible. See Boothroyd et al. [1994] and Bralla [1986].

Design for casting: Two major advantages of casting are (1) producing intricate shapes such as undercuts, complex contours, and reentrant angles and (2) allocating materials according to stress distributions of the parts. Depending on the actual mold used, its suitable production volume ranges from low to high. The major design considerations for casting are flow and heat transfer of the material. Try to design the parting line on a flat plane if possible, use uniform cross-section (Fig. 13.22A), and round corners to avoid hot spots (Fig. 13.22B). See Boothroyd et al. [1994] and Bralla [1986].

Design for Injection: For intricate parts that are not subject to high stresses, injection molding is the best candidate. It is a process for large-volume-production. Allow sufficient spacing for holes and making the main wall of uniform thickness. See Boothroyd et al. [1994] and Bralla [1986].

7. Reparability, maintainability, human factors, and safety issues are discussed in [Anderson, 1990]. See also Compton [1996] for general discussions on DFM.

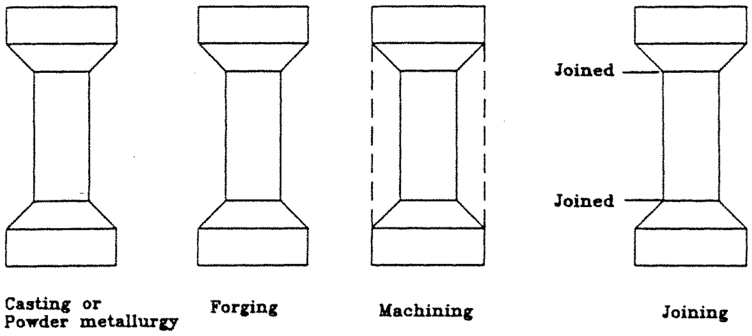


FIGURE 13.23 Different manufacturing processes for the same part.

TABLE 13.12 Comparison of Different Processes

Possible Manufacturing Processes	Casting, Powder Metallurgy	Forging	Machining	Joining (Welding, Brazing, Bonding)
Special tooling	Yes	Yes	No	No
Materials wasted	No	No	Yes	No
Comments	Net, near-net shape processing; good for large-volume production	Net-shape processing; improved strength; good for large-volume production	Economical for low-volume production; choose the materials such that materials wasted be minimal	Most appropriate choice if the tops and middle portion are made of different metals

Integration of CAD and DFM

The *greatest* benefits of DFM can be attained when DFM guidelines are applied in *early* design stages, while the current CAD system has been oriented to detail design. Research is needed to lay the foundation for the CAD system for the conceptual design so that DFM and CAD can be integrated successfully. Mukherjee and Liu [1995] proposed a method that is promising.

Application Examples

Process Selection

The product to be manufactured is shown in Fig. 13.23 and the materials are metal to satisfy the functional requirements. To manufacture a cost-competitive, high-quality product, it is important that the part be produced at net or near-net shape, which eliminates much secondary processing and reduces total manufacturing time and lower the cost. The process selection also depends on production volume and rate. See Table 13.12 for a comparison of different processes.

Reticle Assembly — The Amazing Improvement of the Product Design through DFA

On the left side of Fig. 13.24 was the original design of the reticle assembly by Texas Instrument and on the right side was the improved design. The comparison of the two design is shown in Fig. 13.25. See Boothroyd, et al. [1994] for detailed discussion.

Evaluation of Manufacturability for Stamped Part in Conceptual Design

Figure 13.26 is an example showing that the design with less bend stage is a better design for stamping. To represent parts for early manufacturability evaluation in computer is an active research area. Figure 13.26 is one way to achieve this goal. See Mukherjee and Liu [1997] for more information.

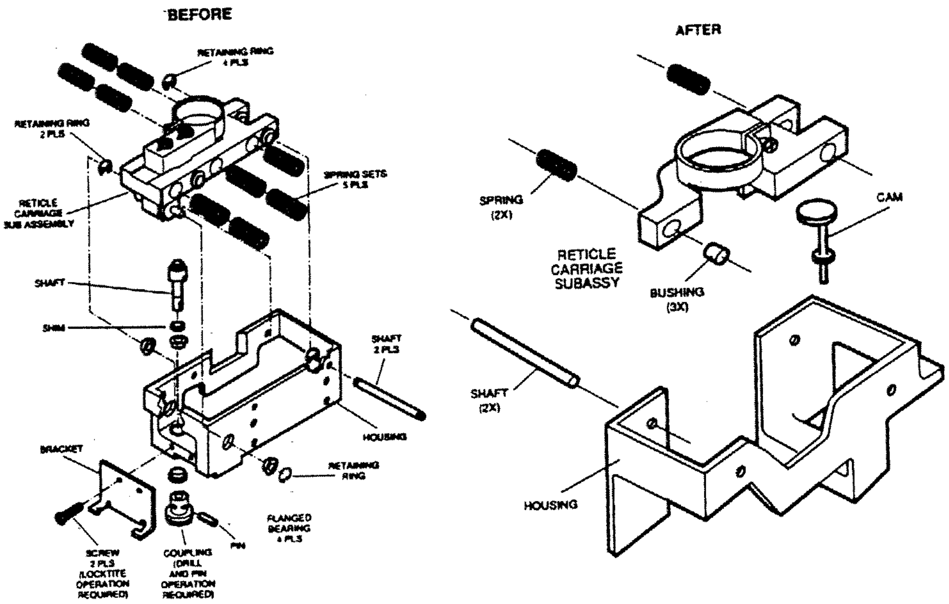


FIGURE 13.24 (*Source:* Boothroyd, G. et al. *Product Design for Manufacture and Assembly,* Marcel Dekker, New York, 1994.)

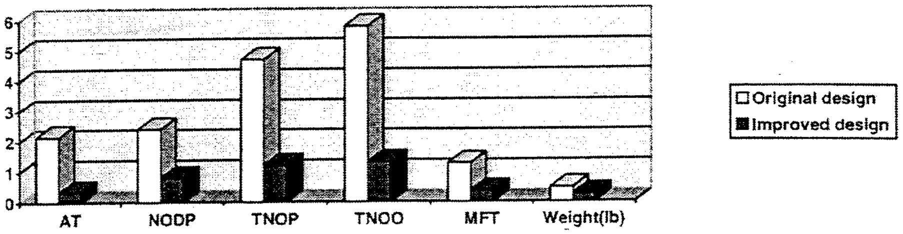


FIGURE 13.25 Comparison of original and new designs of the reticle assembly. AT: Assembly time (h), NODP: Number of different parts (×10), TNOP: Total numbers of parts (×10), TNOO: Total number of operations (×10), and MFT: Metal fabrication time (h). (*Source:* Boothroyd, G. et al. *Product Design for Manufacture and Assembly,* Marcel Dekker, New York, 1994.)

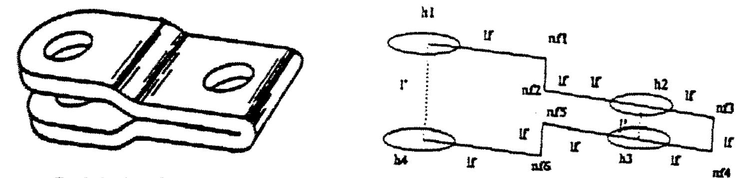
Defining Terms

Computer-integrated manufacturing: A methodology to integrate all aspects of design, planning, manufacturing, distribution, and management by a computer.

Concurrent engineering (CE): To integrate the overall company's knowledge, resources, and experience in design, development, marketing, manufacturing, and sales at the earliest possible stage so that the product developed can be brought to market with least time, high quality, and low cost, while meeting customer exceptions.

Design for manufacturability (DFM): The practice that brings the consideration of manufacturing issues into early stages of product design process to insure that all issues are considered concurrently so that the product can be made in the least time with the desired level of quality and the least development cost.

Value analysis(VA): A system of techniques that use creativity and the required knowledge to provide each function for lowest cost by identifying function and evaluating function.



Bad design for stamping

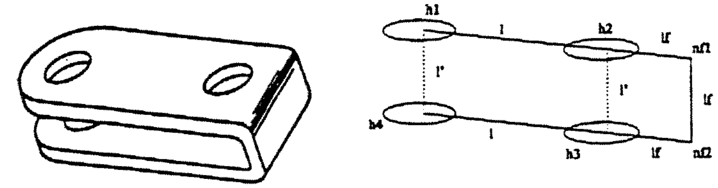


FIGURE 13.26 (A) Examples of stamping parts. (B) Parts sketching abstraction that facilitates manufacturability evaluation in conceptual design. (*Source:* Mukherjee, A. and Liu, C. R. *Res. Eng. Des.*, 7: 253–269, 1995.)

References

Anderson, D. M. *Design for Manufacturability,* CIM Press, Lafayette, CA, 1990.

Boothroyd, G. et al. *Product Design for Manufacture and Assembly,* Marcel Dekker, New York, 1994.

Bralla, J. G. Handbook of Product Design for Manufacturing, McGraw-Hill Book Company, 1986.

Compton, W. D. *Engineering Management, Creating and Managing World-Class Operations,* pp. 264–307, Prentice-Hall, Upper Saddle River, NJ, 1997.

Jacobs, G. Designing for improved value, *Engineering,* February: 178–182, 1980.

Kalpakijian, S., *Manufacturing Processes for Engineering Materials, 3rd ed.,* Addison-Wesley, Menlo Park, CA, 1996.

Liu, C. R. and Mittal, S. Single-step superfinishing hard machining: feasibility and feasible cutting conditions, *Robot. Comput. Integr. Manuf.,* 12(1): 15–27, 1996.

Mukherjee, A. and Liu, C. R. Representation of function-form relationship for conceptual design of stamped metal parts, *Res. Eng. Des.,* 7: 253–269, 1995.

Mukherjee, A. and Liu, C. R. Conceptual design, manufacturability evaluation and preliminary process planning using function-form relationship in stamped metal parts, *Robot. Comput. Integr. Manuf.,* in press.

Shina, S. G. *Concurrent Engineering and Design for Manufacture of Electronics Products,* Van Nostrand Reinhold, New York, 1991.

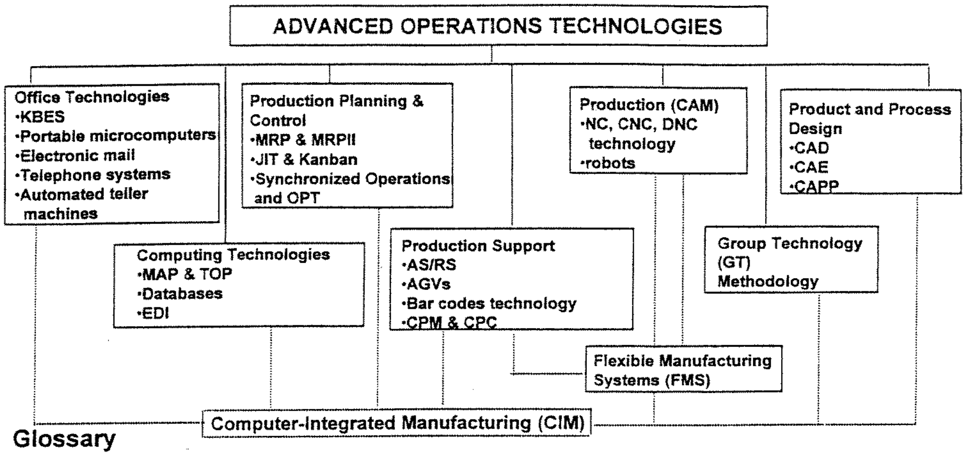
Trappey, A. J. C. and Liu, C. R. An integrated system shell concept for design and planning, *J. Des. Manuf.,* 2: 1–17, 1992.

13.11 Computer-Aided Design and Manufacturing

Hamid Noori

Computer-aided design (CAD) and manufacturing (CAM) are defined by the use of computer software and hardware to assist in the manufacturing process. Inasmuch as the software is used to "drive" the production machinery in CAM, CAD is the use of software and hardware to assist in the design process.

CAM is not an entity unto itself, but simply the use of computers in the context of the manufacturing process. According to the *Automation Encyclopaedia,* CAM involves many disparate activities, including on-line planning, computer-numerical control (CNC), automated assembly, computer-aided process planning, scheduling, tool design and production, automated materials handling, and robotics.



Glossary

KBES -Knowledge-based expert system
MAP -Manufacturing automation protocol
TOP -Technical and office protocol
EDI -Electronic Data Interchange
MRP -Materials requirements planning
MRPII -Manufacturing resource planning
JIT -Just-in-time
OPT -Optimized production technology
CAM -Computer-aided manufacturing
NC -Numerical control
CNC -Computer numerical control
CAPP -Computer-aided process planning
DNC -Distributed numerical control (or direct numerical control)
CAD -Computer-aided design
CAE -Computer-aided engineering

FIGURE 13.27 A list of advanced operations technologies.

CAD/CAM is a fundamental requirement for the implementation of a computer-integrated manufacturing (CIM) or, ultimately, an enterprise-wide manufacturing system (see Fig. 13.27).

A Brief History of Automated Production Processes

The use of automation in manufacturing can be traced back to the early 1800s, when Joseph Jacquard produced a fabric loom capable of running with a card system to produce patterned fabric. The mechanization of the factory proceeded throughout the 1800s and early 1900s. The introduction, in the early 20th century, of the assembly line created the perfect medium to accelerate the growth of controlled production processes.

The introduction of numerical-control (NC), in the 1920s and 1930s, expanded the application of card-directed production. By the late 1950s and early 1960s the use of a "computer-directed" manufacturing process had become fairly widespread. With the evolution of computers came the vastly expanded application of CNC production.

Moving into the late 1960s and early 1970s, as the cost of automation and computer-assisted applications dropped, the uses of CNC expanded rapidly. The wider availability of personal computers (PC) in office and manufacturing settings created the next wave of application adjustments to the automation of the production process.

Concurrently, the development of CAD in the late 1960s began what can be best described as the second prong of the CAD/CAM development process. The 1970s saw the increased integration of the two applications, so that they are now thought of as permanently linked.

What Is CAD?

CAD refers to the use of a computer to create or modify an engineering design. Traditionally, the designs, and supporting tooling for a product, were done on a drawing board. An engineer would prepare a blueprint manually for the total product, including the tooling to produce the product. Other engineers would provide the drawings for their specialized area, (i.e., electrical). These would be used throughout the product development process and updated or changed as the process continued. This process was

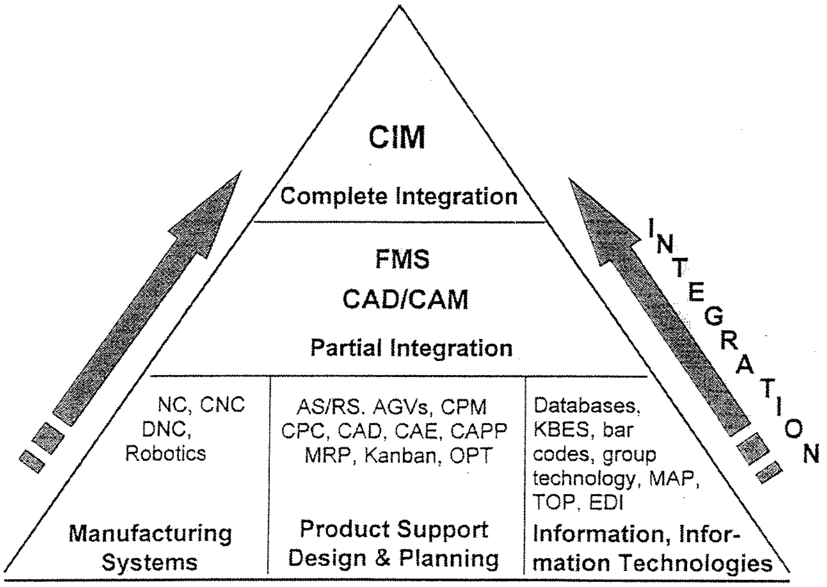


FIGURE 13.28 CIM.

very costly in terms of time and money. CAD has improved the process significantly and reduced dramatically the development costs and time.

What Is CAM?

CAM is a generic term used to describe the complete range of computer applications in direct manufacturing activities. At the heart of CAD/CAM is the linkage of the design process to the machine programs of the manufacturing facility. The effectiveness and efficiency of this linkage has been one of the prime reasons for enhancing the accuracy and reliability of the product development process, shortening the manufacturing process times, and hence shortening the product introduction time and improvement in overall productivity.

Computer-Integrated Manufacturing

The integration of CAD/CAM with other technologies such as computer-aided engineering (CAE), group technologies such as computer-aided process planning (CAPP), CNC, appropriate databases, and the like, when used concurrently, are commonly known as computer integrated manufacturing (CIM). Organizations today are in the process of automating the production process ranging from automation of specific functional areas to full integration (see Fig. 13.28).

Enterprise-Wide Automation Systems

The development and use of enterprise-wide automation systems are a phenomenon of the late 1980s and early 1990s. At the heart of these systems is the linkage of some, most, or all internal functional areas, often including upstream suppliers and downstream customers (see Fig. 13.29). For example, in the case of the **CATIA** system (computer-aided, three-dimensional, interactive application) used by Boeing in the development of the 777 airframe, the ability to develop, on-line, the various parts saved time and money. The 777 is the first Boeing airliner to be 100% designed using three-dimensional (3-D) solid modeling technology. The software enabled Boeing to design, model and adjust the design on-line. CATIA promotes concurrent engineering, on-line, in 3-D — linked to the appropriate databases. The

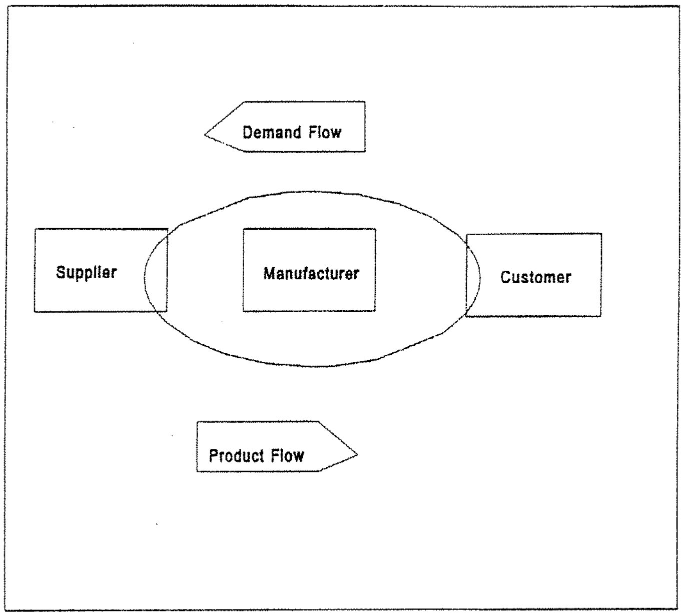


FIGURE 13.29 Enterprise-wide linkage through the value chain.

result of Boeing's use of the CATIA system was an aircraft that was developed in a much shorter time frame and at substantial cost savings. Boeing has since moved toward the integration of the entire organization into an on-line information technology system, ultimately creating the ability to track virtually any item.

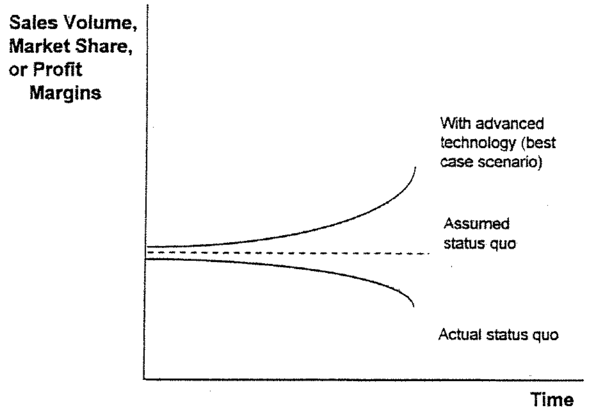
Manufacturing Technology and Strategy

The search for ever tighter quality control and cost containment is creating the push for the use of manufacturing technologies. In essence, firms are no longer competing on cost or quality alone; they are competing on the total value provided. Whoever delivers the greatest possible value is the winner in the marketplace. It is difficult to imagine a firm being able to compete on multiple dimensions of competition (price, quality, flexibility, time, etc.) simultaneously without using some form of automated technologies (such as CAD/CAM). In fact, it is argued that adoption of new technology could have a major impact on the operational effectiveness of the company enabling it to compete more effectively on multiple dimensions of competition. At the same time, it is also important to note that any decision to adopt new technology must be embedded in the operational vision and overall strategy of the firm.

Strategy is the creation of a valuable position, involving a unique set of activities that determines how, where, when and for what type of customer a firm is going to compete, and what type of organizational structure the firm will require. In this context, choice of appropriate manufacturing technology is vital to the success of the firm. This implies that it is not enough for a firm to merely duplicate a competitor's manufacturing automation. Instead, it should base its decision on the fit between the technology and its strategy.

Investing in Advanced Manufacturing Technology

The decision to employ advanced manufacturing technologies is no simple task. Indeed, the costs, in terms of time, money, and commitment are considerable. However, the cost of *not* investing in these technologies may be greater.



Message: Do not automatically assume that the firm's competitive position will remain as is if investments in advanced technology are **not** made. Also, do not assume that if investments in advanced technology are made, the line will slope upwards; these investments may be necessary just to maintain the status quo. The upwards sloping line may be the best case scenario. The true slope will depend upon the success (or failure) of the implementation vis-a-vis the competition. The slope of the actual status quo will also be influenced by the actions of the firm's competitors.

FIGURE 13.30 A Comparison of investment in advanced technology vis-a-vis maintaining the status quo. (*Source:* Adapted from Noori, H. and Radford. *Production and Operations Management: Total Quality and Responsiveness*, p. 287, McGraw-Hill, New York, 1995.)

Consider the situation whereby a competitor invests in new technologies that improve quality, cost, or both, effectively changing the value equation of the product. The options available to the target firm are limited to investing, not investing or attempting to redefine the value equation. In most industries, the options will be limited to, in the short run at least, investing or not investing. The decision then becomes: "Will the customers accept the product the firm currently delivers?" Once the market becomes aware of the changing value equation, the target firm will no doubt face erosion of the customer base. The firm, in actual fact, has no real option to maintaining the technology status quo (see Fig. 13.30).

Financial justification of new technology is usually a challenging job. This is so because many of the costs (such as software development and maintenance and productivity decline in transition) are hidden and some of the benefits (such as strategic flexibility) are not easily quantifiable. Attention to these hidden costs and deciding who should establish the (surrogate) criteria and specification to justify the acquisition are therefore important. In general, to justify new technologies, one can think of those benefits and costs that can be identified, quantified, and, finally, to which financial measures can be applied.

Concluding Remarks

The purpose of this section was to provide the practitioner with a snapshot of the issues involved with CAD/CAM and other manufacturing automation technologies. New technologies often provide increased flexibility and capability. For firms competing in dynamic, often chaotic environments, the creation and retention of a competitive advantage may lie in the utilization of advanced technologies. Flexibility or agility may be the deciding factor for which firms survive and prosper and those that do not in the future.

13.12 Total Quality Management

B. Michael Aucoin

Total quality management (TQM) is in many ways the heart of any endeavor, for it involves organizing for and delivering the inherent worth of a product or service. Continually improving the quality of a product or service is critical for the success of an organization and should be a key element of its business strategy. There are two major foundations to TQM. One is analytical and involves the management of variation from specification. The second is organizational and relates to the management of the value or worth of a product or service. The organizational aspect also involves working to continually improve the product or service and the environment in which it is produced. In brief, TQM is identifying what customers want and organizing to provide what they want.

Progress of Quality Movement

Anyone who has followed popular management over the last 15 years has seen much discussion and activity concerning TQM. During this period the quality movement reached its zenith with scores of books, conferences, and seminars on the subject. Recently, the level of activity has declined, signaling the rise and fall of faddish TQM and the firm establishment of genuine TQM.

For much of the 20th century little thought was given to product quality as customers were expected to buy whatever was offered. In large part this can be attributed to the dominance of U.S. goods in the world until the 1970s. With little competition, there was little reason to provide high quality. Where quality was considered important, it was typically approached as inspection for defects after production, based upon the belief that production workers had little interest in product improvement.

Two key developments led to the progression of the quality movement. First, after the devastation of World War II, Japan embarked on a commitment to quality manufacturing with the help of W. Edwards Deming, the father of the quality movement. With their rise and the rise of other nations with resulting competition for markets, and reduction of barriers to market entry, quality became a means for product differentiation. Ultimately, in the 1980s, the quality movement reached the United States as it finally recognized the need for instilling quality in products.

Second, in the development of management practice, it came to be recognized that all individuals in an organization can have a significant impact on quality and productivity. This understanding began with the landmark Hawthorne studies in the 1920s but did not reach fruition until the 1980s. This simple but fundamental shift in thinking became an important cornerstone of implementing quality in organizations, making quality the responsibility of everyone in an organization.

There is little argument that the quality movement has resulted in significant improvements in products and customer satisfaction. However, TQM as a movement has had mixed results. If so, why? The organizations that failed at TQM never really implemented it and instead approached it as faddish window dressing. TQM when sincerely implemented will result in demonstrable improvements in product or service quality, customer satisfaction, and organizational success.

Defining Quality and TQM

One can come up with various definitions for quality, but in fundamental terms quality involves satisfying a customer. Quality is whatever a customer says it is and may differ from one customer to another. While most people have a rough concept of quality, one can define it as appropriate functions, features and workmanship for a customer target cost. For this definition, quality does not necessarily imply the product with the most features or the highest cost, but the one that does the best job for a given price. The quality of a product or process is best approached by identifying characteristics that can be measured.

Simply speaking, TQM is the identification of what a customer wants and organizing to deliver what the customer wants. The identification of customer requirements is the result of research on customer preferences and is embodied in the product specification. Organizing for quality involves establishing the organizational systems for making quality a critical aspect of a product or service and providing the environment for delivery of quality.

At any given time the specification defines what the product should be as an understanding of what the customer wants. It defines in measurable quantities the features, function, and operation of the product under various constraints including price. The customer's expectation of the product is embodied in the specifications.

If the specification embodies customer preferences, then any variation of a product from specification can be considered a defect with an opportunity for improvement. This definition of quality and organizing to provide this aspect of quality involves analysis and feedback to production. By applying appropriate tools and techniques, variations in product quality can be readily identified and corrected in production.

The specification is best seen as a dynamic document, and, at any point in time, it is a snapshot of customer needs and the organization's best thoughts on how to meet them. However, customers, organizations, and technology are dynamic entities so there is always room for improvement. In this aspect of quality management, organizations strive to improve the inherent merit or worth of a product. Is the product what it should be? How can it be improved? In essence, this definition of quality occurs outside the specification and drives the specification as a feedback mechanism.

It can be seen that there are two ways of influencing or improving product quality: one is analytical and the other is behavioral or organizational. These two approaches will now be discussed.

Process Quality Management

Let us assume that we have a specification for a product and a process to produce it. We want the output of the process to conform to the specification. Output that does not comply with the specification within a given tolerance range is defective. The foundation of analytical quality management is taking data on a process to gain knowledge about the capabilities and limitations of the process. Based upon this knowledge we can ultimately control a process, that is, make it behave in the way we want it to behave, or in conformance to the specification. We want to have a process that is stable and predictable, so that it can always produce products in the same range of characteristics.

The tools of analytical quality management permit drawing conclusions about the quality of a process based upon sampling of the process. By implementing process quality management, we can make the transition from *detection* of defects to *prevention* of defects and thereby make dramatic improvements in quality (as conformance) at a reasonable cost. The act of measurement produces a feedback mechanism to the process that makes prevention possible. One of the other benefits of analytical quality management is that it enables the involvement of everyone associated with the process, not just the inspector.

One of the primary tools for analytical quality management is **statistical process control** (SPC), a methodology pioneered by Walter A. Shewhart in the 1920s, which involves a statistical sampling of measurable parameters of a process output such as products coming off a production line. A process that is operating properly produces outputs that exhibit some slight variations from one unit to another, but the overall average of a particular parameter should be stable. If there are excessive variations in the parameter, there may be defects that will result in lowered quality as perceived by the customer.

By examining the characteristics of variations, one can see whether the process is predictable in its behavior or under **statistical control**. A process is brought under control by eliminating or correcting all special causes of variation, such as operator error or power surges, which cause excessive variations. This procedure is accomplished by eliminating, one by one, special causes of excessive variation. The primary tools of SPC are the run chart, which depicts the measured values of a product characteristic over the course of a process run, and the control chart, which builds upon the run chart to permit one to visually determine if the process is under control.

Just because a process is under control does not mean it is necessarily producing the desired output. After bringing a process under control, the next step is to ensure that all variations are within tolerance. When this is achieved, the process is said to be **capable.** A process is made capable only through improvements in the process itself.

Even after a process is under control and capable, it is important to seek to improve the process. One principle of process improvement, initiated by Genichi Taguchi, holds that quality is not just conformance to specification within tolerance but is better described by the deviation from target value. One should seek to minimize the deviation from the target value because the quality of a product quickly degrades as a measured characteristic deviates further from the target value.

A powerful method for improving process quality is through **design of experiments** (DOE). This is a statistical method that interrogates the process to help optimize it. It involves making deliberate changes to inputs based upon statistically designed, orthogonal experiments to determine the effects of inputs on outputs. Through experimental design, one can screen the process to determine the factors that most affect the process and how they do so. Experimental design enables one to model the process and determine the sensitivity of the process to key input factors. Based on this information, one can optimize the process and make it more robust.

In addition to the numerical tools of SPC and DOE, there are many other valuable non-numerical techniques and tools for management of quality. Some of the other tools used for prevention of defects and quality management include

- Cause and effect (Ishikawa) diagram — a diagram often used in a group setting to identify causes and potential solutions of a problem.
- Flow chart — a chart that depicts activities and steps in a process to identify points at which improvement is needed.
- Pareto chart — a chart used to concentrate efforts on the few issues that contribute significantly to a problem rather than the many trivial issues that have little effect on a problem.
- Quality function deployment — a map of customer requirements into technical product characteristics, also called a "house of quality".

Continuous Improvement

It may be apparent by now that the pursuit of quality is an ongoing and never-ending mission. This aspect of quality can be described as the continuous improvement dimension of quality. For many products, there is some interaction or feedback from customer use to identify areas for improvement. Often, technological improvements are made and suggest application to the product. The best products are delivered in environments that solicit customer input, survey the environment for technology developments, and apply creative thinking, all in a mechanism that feeds back into the next round of product specification.

Organizational Aspects of Quality

Products and services are provided by people and often as part of the activity of an organization. It is therefore relevant to consider how individuals and groups affect quality. If TQM is determining what the customer wants and organizing to deliver what the customer wants, then the key word in TQM is *management*. The management of quality involves three key organizational dimensions: focus on the customer, the mission and model of the organization, and team commitment.

Focus on the Customer

The foundation of organizing to deliver what the customer wants begins and ends with the customer. The process of product and service delivery ultimately involves the satisfaction of a customer in a marketplace interaction. While there are many methods to research customer preference and satisfaction, organizations that do well at customer satisfaction go beyond these methods to get close to the customer and to experience the product or service as a customer would.

Consider the 1991 movie "The Doctor", which was directed by Randa Haines. In this movie, the main character is a physician who, while medically proficient, does little to interact with patients on an emotional level. When he becomes seriously ill, he is forced to become a patient and experience the impersonality and dehumanization he had delivered as a doctor. He recovers and returns to practice as a doctor who has learned to care about the patient as a human. Not only is the story moving, it is a dramatic lesson in learning how to deliver better service to a customer.

The best organizations live and breathe customer orientation, and they try to live the interaction from the perspective of the customer. There is still more to the story, however. The holy grail of customer satisfaction comes in delivering a product or service in such a way that is uniquely outstanding. It goes far beyond a feeling of satisfaction in the customer and results in the customer perceiving the transaction as exceptional. Tom Peters [1994] describes this as a "WOW" experience.

One example of this exceptional level of customer satisfaction is provided in *The E-Myth* by Gerber [1986]. He describes an accidental stay at a California inn that does an exceptional job at meeting and even anticipating his needs.

The staff watches when he leaves his room for dinner so that a lighted fire can be prepared for him before his return. He orders a brandy at dinner, and, without his asking, the staff has a second glass waiting next to his bed upon his return. In the morning his favorite coffee and newspaper are made available without his asking. Through observation and subtle questions, the staff learns how to tailor the lodging experience to each guest and provide key ingredients of the experience without being asked, *exactly when the guest anticipates wanting them.* The service is so exceptional that Gerber is awestruck. We are generally used to accepting mediocre customer service as the standard in our society. When we encounter exceptional service, it can transform us.

Organizing for Quality: Mission and Model

If we can determine what the customer wants, and we wish to provide an exceptional customer experience, how then can we organize to deliver it? One starts with the mission or core beliefs of the organization. Again, one example can be found in the story of the inn described in *The E-Myth.*

The manager of the inn explains that the goal of the staff is to provide an experience for the guest that replaces the home that most of us no longer have. The structure of the organization provides the lodging service in the context of a system, a game that is played to provide the sense of community and love that is present in what we would like to experience at home. The best quality organizations speak about the customer with a passion and organize systems, resources, and policies around this passion.

If having a quality organization is the vision, what are some ways of implementing this vision? Ultimately, there must be a singularity of purpose for the all members of the organization to strive to deliver quality products and processes to the customer. If the "soul" of the organization embodies a passion for customer happiness, the rest becomes easy. It is important for the organization leadership to exhibit this passion in behavior and attitude. For example, Herb Kelleher, CEO of Southwest Airlines, regularly does his part to load baggage and perform other tasks that bring him in direct contact with the customer experience.

Next, the leadership must implement a good model for the organization. A model for this purpose can be considered a set of process and operating principles and strategies that implement the core beliefs into the workings of the organization. To promote quality, the model for an organization should embody and strive to build an environment that values the delivery of quality to the customer, promotes honest communication, allows members to adapt the model to their specific situation, and provides sufficient resources to implement the model.

The organizational arena of quality provides the opportunity for success, but many organizations have failed in their efforts to implement TQM programs. If this is the case, what can go wrong with TQM?

The road to quality leads through humility or even pain because the pursuit of quality means always admitting that there is room for improvement. Many individuals and organizations are unwilling to admit their need for improvement, and, for this reason, they never seriously pursue quality. It is easier for them to talk about quality rather than do something about it. This is the essential difference between organizations that practice faddish quality and those which practice genuine quality: quality organizations don't just talk about quality, they live it.

It is relevant in this context to mention standards for quality, such as ISO 9000. These standards have been developed for systematically organizing, developing, and documenting an organization's processes and systems for delivering quality. These standards are valuable as guideposts, but they do not in themselves guarantee quality and do not substitute for the pursuit of genuine quality in an organization.

Team Commitment

For organizations that commit to genuine quality, the final organizational issue to address is obtaining the commitment of the members of the organization to implement the vision of quality. To be effective, quality management requires all members of an organization to contribute to continuous improvement. Such a commitment cannot be forced; it must be voluntary. The good news is that individuals in organizations desire meaning in what they do and want to be valued and successful. It is the responsibility of the leadership to build organizations and systems that promote such an environment. With this approach, individuals willingly commit to providing their best creative effort for the success of the endeavor in pleasing the customer. There is something worthy, almost transcendent, for individuals in following a good model.

There is a story about three bricklayers. One describes his work as laying bricks, another as constructing a building. The third explains that he is erecting a cathedral that will inspire many. It is in seeing one's work in such a model that leads to exceptional service delivery among individuals in an organization.

Conclusions

The pursuit of quality is a crucial core component of the mission of an organization. There are two major attributes of quality management: first, managing the quality of a process and, second, managing the continuous improvement of the behavior of the organization. TQM is implemented by continually identifying what customers want and organizing to deliver what they want. With the choices available to customers in the marketplace, organizations that do well at managing quality have a decided advantage over those that do not.

Defining Terms

Capable: A state of a process that is achieved when all variations in the process output are within tolerance.

Design of experiments: A statistical methodology for determining the effect of process inputs on outputs so one may improve or optimize the process.

Statistical process control: A statistical methodology for determining if a process is performing within acceptable parameters.

Statistical control: A state of a process that is achieved when all special causes of variation in the process output have been eliminated and the process is stable.

Total quality management: The identification of and organizing to deliver what a customer wants.

References

Gerber, M. *The E-Myth*, Harper Collins, New York, 1986.
Peters, T. *The Pursuit of WOW!*, Random House, New York, 1994.

Further Information

There is a multitude of reference materials available on quality management. Books that provide extensive coverage of the subject include *Total Quality Control* by Armand V. Feigenbaum and *Total Quality Management Handbook* by Jack Hradesky.

Those interested particularly in TQM in a production environment would likely benefit from H. G. Menon's *TQM in New Product Manufacturing* as well as *Improving Quality through Planned Experimentation* by Richard D. Moen, Thomas W. Nolan, and Lloyd L. Provost.

A study of quality should include review of work by W. Edwards Deming, such as his book *Out of the Crisis* and *The Deming Guide to Quality and Competitive Position* by Howard and Shelly Gitlow.

It is also helpful to engage in a critical examination of TQM successes and failures in *Why TQM Fails and What to Do About It* by Mark Graham Brown, Darcy E. Hitchcock, and Marsha L. Willard.

The organizational aspects and customer orientation of quality are addressed well in Michael Gerber's *The E-Myth* and *The Pursuit of WOW!* by Tom Peters.

The American Society for Quality Control is an excellent resource for information on quality through their monthly publication *Quality Progress.*

13.13 Process Improvement: The Just-in-Time Effect

Robert W. Hall

Just-in-time (JIT) production is the father of time-based management principles. JIT techniques are frequently rediscovered and applied to all kinds of processes under such names as concurrent engineering, one-stop customer service, reengineering, and others. Because of the tangible nature of machines and materials, the principles and techniques are easier to see in a production process.

One of the most unfortunate aspects of JIT production is its name, which implies that its objective is merely to make material arrive at each step of a process just in time to be used. That is only one observable result. The objective is to improve manufacturing quality, efficiency, and responsiveness to customers.

JIT prods continuous improvement in many forms and many places, not just the production floor. Through extension to a supply chain, the intent is to eventually cover a total process — from minerals in the ground to the end user. To prepare people for collaboration and continuous improvement, JIT development is usually accompanied by development of teamwork in some form. It's a mind set change.

Just-in-Time Principles

JIT is an unending improvement process that can be perceived in many ways. Its principles are flow, visibility, and compression of operations. Application of the principles depends upon the specifics of each case.

A first step in mind set change is to measure performance using time. In a plant, one measure is throughput time, the lead time from material starting production processes until it finishes. A broader measure is door-to-door time, from material entry to customer shipment. In most plants, these measures are approximated using days-on-hand inventory. In addition, order-to-ship time measures the customers' experience.

Another measure is value added ratio, the fraction of throughput time during which value is added (synthesis, fabrication, or assembly). Time consumed not doing value-added work correctly, or in doing anything else, is wasted. Activities that waste time are targeted for elimination. Simplify the manufacturing process into its essence, stripping away any activity that does not need to be done.

A plant that has never thought about JIT often has a value-added ratio of 5% or lower. A stretch goal could be to attain a value-added ratio of 50% or higher, depending on the potential inherent in the production process. Like snowflakes, many plants are similar, but none are identical.

Waste has been categorized in many ways: quality, idle inventory, poor equipment maintenance, unnecessary material handling, poor training, absence of information, or floods of it, and on and on. There is no formula for eliminating waste other than cutting lead times (inventories) to make problems so visible that they receive attention. Some problems are easily overcome. Others continue to foil solution after repeated attack, but the dictum of JIT is straightforward. Solve anything solvable, and never sink back into addiction to that drug of manufacturing, excess inventory.

Well-developed JIT production processes have little excess motion. Operations with a high value-added ratio have a minimum of conveyor belts, material handling, clutter, and confusion. Expediting isn't a crisis. Like good athletes, people using processes that add much value make it look easier than it really is.

People who mimic a few JIT techniques fail, or at least they never realize anything close to their potential. Those who succeed understand that the techniques support human development by stimulating problem seeing and problem solving. Those responsible for processes learn experientially. Even if new plants are laid out for fast flow using equipment designed it, operators must see their problems themselves, and largely overcome them themselves. You cannot successfully "hand" JIT to them.

Managements that have removed great waste have developed their people — the entire workforce, white collar, blue collar, or pink collar — to work together recognizing and solving problems. It's usually called teamwork and quality. There's no point cutting inventory to reveal problems if the organization isn't prepared to deal with them. Changing performance measurement, reward systems, and traditional roles of people — the "soft stuff" — is more difficult than adopting JIT techniques.

This prepares minds for JIT. Then simplify, simplify, simplify the processes themselves. Next, control operations by decentralized parallel processing (by people, not just computers) rather than by a centralized brain issuing orders.

JIT Techniques

The following brief review of techniques assumes that minds are prepared and that an existing manufacturing process is to be converted to JIT. The techniques still apply if one is designing a JIT process from a clean sheet of paper, no matter how manual or automated it may be. No process is perfectly designed from scratch. All need tuning, and, as requirements change, all need adaptation.

Workplace Organization, or 5S

The shorthand version of this is "A place for everything, and everything in its place, free from extraneous items." There are different versions of the five steps, but a common one is:

1. *Clearing and simplifying*: Remove everything unnecessary in the near future. Besides trash, that includes tools, materials, and instructions. Reduce each work place to the items essential to its functioning.
2. *Standardizing locations*: Think of surgical trays. Colocate everything used together, ready for use, and easily found by anyone (or any machine) that needs it: often-used items in standard spots for instant use, less frequently used ones at a greater distance, and rarely used ones stored away. Silhouette tool boards throughout a plant are a common marker of this practice. This discipline begins to develop *visibility* in the workplace.
3. *Cleaning*: Clean regularly so that dirt or accumulated offal never interferes with process functioning, whether it's in a class 10 clean room or a foundry.
4. *Discipline to maintain the system*: For workplace organization to be effective, everyone involved must learn the discipline of the system and follow it.
5. *Participation*: Everyone must understand and support the system, which means that no one — executives, engineers, etc. — messes up an organized workplace. Everyone cleans up after themselves.

Visibility

This is unspoken, often unwritten human communication. In a plant or a project office, anyone should be able to evaluate the situation at a glance: flow of material, inventory levels, machine status (by signal lights), goals, orders, schedule, and accomplishments. Disruption of an expected pattern of visibility is a cue that a problem exists and that it needs attention. A good visibility system displaces the need for managers and supervisors to intervene in routine operations. The shop floor runs itself.

The implications run deep. If a set of operations becomes a shared, readable environment to its participants, people are drawn to becoming students of the process and more willing to participate not only in its preservation, but its improvement.

Properly applied, computers, software, and sensors enhance visibility (and control processes) in ways that are impossible by humans alone. Poorly applied, they complicate the environment without removing waste. The need for human visibility suggests man-machine (and man-software) interface issues roughly analogous to those of pilots flying by computers and instruments rather than manually by visual rules.

Disciplined Pull Systems

A pull system of production control means that each production station signals its preceding stations what material or other items that it needs. If the pull system is disciplined, it also limits the volume of inventory in the pipeline between all pairs of work stations. Limiting the pipeline stock also limits the production throughput time. It also limits the time window within which each station must respond to the demands of its "customer" stations, which stimulates people to pay attention to eliminating waste in order to do it.

The signaling system is often called a kanban system, which can be set up in a variety of ways. In the simplest case, a part is simply transferred one at a time from one station to the next, by a person or by a device, sometimes a conveyor. If the storage space between stations is limited, the inventory is also limited, and knowing what part to send is elementary. It is the only one exiting the machine and going to the next.

One step up in complexity, a little larger space is marked into squares or compartments, one square being designated for each part number and limited in size. The supplying station simply fills open squares that have been emptied by the using station. This simple system is merely one aspect of an overall shop visibility system.

If a supplier station is out of sight from its customer stations, the signals may be conveyed using cards, or standard-sized, designated parts containers — empties returned from the customer. These signal the need to replace a fixed number of parts withdrawn from the pipeline. Thus, the range of the visibility system can be extended to customer sites many miles distant, but the inventory in the pipeline remains limited if the number of cards or containers in circulation for each part number is limited.

With the basic idea of a disciplined pull system in mind, imaginative people may concoct varying mechanisms for signals and inventory limits, including electronic ones, but the key point is to maintain pressure for process simplification rather than be diverted into fancy systems to manage waste.

An objection to this system is that it will not work unless process routings are standardized, and that is true. There are two response to this objection. First, if process routings could be standardized, but they have grown up in a tangle, that is itself a waste, and needs to be corrected.

Second, disciplined pull systems are only one aspect of visibility. Engineer-to-order job shops and process industries not having discrete parts are both subject to great improvement using all the other ideas of JIT, including simplify, simplify, simplify, visibility systems, and as much parallel processing as can be built in. This is more than a speculative concept; it's been done.

Setup Time Reduction

As long as setup times are long, lot sizes do not decrease much. Therefore, neither inventory or throughput times decrease very much. Setup processes are attacked the same way as any other, by eliminating the waste. First, eliminate any steps that are unnecessary, and apply 5S to setup processes. Then reduce the operations that must be done with the machine stopped to the barest minimum.

Without changing process technology or product designs, reorganizing the physical process of setup may cut setup times by 50 to 90 and even 100%, and all with a decrease of work required, not an increase. Sometimes maintenance and quality are issues. The objectives of quick setup are to make a quality piece the first time with no adjustments and to keep maintenance separate from setup. JIT stimulates plants to adopt preventive and predictive maintenance. The specifics of each setup must be worked through, but thousands of plants have now done it.

Common issues are broadening the training and responsibility of workers, therefore reducing the number of job classifications, and organizing workers into teams for setups. The human legacies are more difficult to overcome than the plant physics, but some of those are also challenges. Single-purpose, dedicated equipment and tooling does not become flexible easily.

Reducing setup times improves manufacturing flexibility as well as efficiency. For example, it may allow the scheduling of new tooling trials without disrupting production.

Attention to setup problems throughout a company stimulates other useful thinking, for example, design for manufacturing and design for assembly, simplicity of process with maximum use of common parts. Another line of thinking is to avoid tooling changes by making as much setup as possible depend only on a change of software — to cut a different path in a workpiece, for instance.

Moving in this direction leads to the idea of giving the customer maximum variety from his viewpoint, but from a standard flow production process. If both the engineering and execution of a customer solution can be done with minimal setup, a plant is in position to not only be JIT, but agile. JIT demands quality, and it improves efficiency and flexibility. Agility is the ability to respond to the unexpected.

Cellular Production

In many cases, one-piece-at-a time flow through a cell is ideal JIT. If all machines in a cell are capable of quick setup, a minute or less, and certainly less than 10 minutes, and if all have a similar routing, a cell can produce a family of parts with a very high value-added ratio.

There are many kinds of cells, which are machines for a sequence of operations grouped together. Some are highly automated; some minimally automated. Cellular manufacturing focuses attention on many issues associated with JIT.

The classic U-line is still the cell design used for reference. An operator moves parts from machine to machine in a walk-around, and he has good visibility and access to the process inside the cell. If the parts are nearly uniform, simple conveyances, such as chutes, can be used between the machines instead of an operator, and the total system can be automated very cheaply using limit switches and the like.

In some cases, an intelligent robot can do this task. However, beware of complexity and cost in programmed automation, particularly if all it does is material handling. Question whether the machine or the software adds value or contributes to waste. Elegant automation adds value. Believing that it must be programmed to handle a large variety of contingencies is evidence that the process has not yet been simplified enough to merit profitable automation. (Complex products have challenge enough without taking on the unnecessary ones.)

Overcoming the problems that discourage the organization of a production process into a cell is the point of JIT, and every case has a full measure of such problems. If machines have not been designed for cells, rearranging them into a cellular layout may be awkward. If people fear not having space to handle all manner of contingencies, machines will be spaced too far apart, which is usually done the first time one organizes a cell. The process needs simplification.

Accounting based on the assumption of totally independent machines and operations is a problem. An expensive machine may lose the volume thought necessary to economically recover its capital and overhead cost. (Keeping expensive machines busy is one of the chief sources of bottlenecks in a job shop. The consequent overproduction adds to waste.) For the same reason, accountants tend to be upset if a machine runs at less than full speed when it is matched with others in a cell. For a financial sanity check, estimate what a cell, plus all the simplification that it necessitates, will do to the total process, not a fraction of it.

However, the greatest challenge again is apt to be the human one. In some cells, it's easy for an operator to learn every operation, and learn preventive maintenance for every machine. In other cells, as for advanced precision machining, this is a stretch. People working in cells must broaden their skills and learn to work in teams, a tough transition made more difficult if historical work agreements and status systems have rewarded specialization.

Kaizen Improvement

Kaizen means seeing and overcoming problems. It takes place in many forms. Employee suggestions, made and adopted, are one form. Immediate corrective action is another form. Schedules in JIT plants often allow a few minutes of downtime each day to observe problems and make corrections, and, if needed, a line, cell, or machine will be stopped immediately while the problem is solved. Anyone observing a problem can stop the process. (The Japanese call this *jidoka.*)

In the United States, kaizen usually refers to a more intensive revision of an area or process for JIT or to make improvements in work flow. Everyone should participate in changing layout and making other revisions that drastically affect their own work.

All the principles and techniques of JIT may be employed in intensive kaizen. A concept very important to kaizen work design is takt time. A takt time is the amount of time allowed to complete all the work for one unit passing through a work station. For example, a line station in auto assembly running at a speed of 48 cars per hour would have 1.25 minutes, or 75 seconds, of takt time in which to properly accomplish work on each car passing through.

Takt time is a scheduled cycle time. Divide the scheduled daily work time available at a station by the number of units to be completed and one gets the takt time per unit. (If one divides the actual time worked by the actual number of units completed, the result is the actual cycle time per unit.)

The objective is to accomplish all the necessary value-added work within takt time. Devise or revise a station work process that eliminates all possible non–value-added work from the work cycle.

Who does this? The worker. When JIT is fully developed, the staff only does preliminary, approximate engineering of work for the workers. Each one finishes his own detailed industrial engineering for his own work station. That is the natural end point of workplace organization.

Again the biggest obstacle is human development, including the development of the managers. Kaizen presumes that almost everyone knows how to make improvement — how to reengineer his work. Problems can be of every kind, quality, time waste, safety, ergonomics, environment, and so on. Many of them cannot be solved by one person alone, or even by a work team in his area, but closely supporting workers in making the detailed improvements is a revolution in thinking.

Learning how to make improvement regularly is a tremendous experience for both individuals and organizations. One does not evolve from a command and control environment to responsibility for improvement quickly. Responsibility means having judgment about costs, so workers need access to appropriate cost databases.

Toyota is still the most advanced company in the practice of JIT. For many years, monthly schedules have come out with calculated takt times for operations, including those that feed assembly and those at suppliers. Using these takt times, the workers revise and improve their stations in preparation for next month's work, a regularly scheduled mini-kaizen. After documenting their plan on standards sheets, they work the plan, and adhering to it is very important.

Toyota calls this distributed production planning. As a consequence, a Toyota assembly plant can change line speed once a month — more often if necessary — a capability that auto companies immature in JIT cannot dream of doing. Only a few other companies have developed JIT this far.

Uniform Load Schedules

For the repetitive manufacturing case, a short description of a uniform load schedule is making a little bit of everything every day. If fabrication feeds final assembly, then the assembly schedule should plan for mixed model assembly, not long runs. Naturally, the assembly process must be physically developed for this also. The lot sizing and uniformity of a schedule should mirror the capability of the physical processes at the time.

Some assembly processes, such as automotive, must run a type of mixed-model sequence in order to maintain line balance. Different models may create overcycles and undercycles of work at various stations. Unless these are balanced out by the sequence spacing, the critical line stations are either starved of work or overworked.

Fortunately, mixed model assembly, or assembly of small-lot batches in a mixed sequence, also creates a relatively uniform demand for the parts that are fed to assembly. Therefore, the pull systems working down through fabrication processes tend to keep all of them working, but with a slightly varying workload. Most operations that have been developed for JIT are robust enough to accommodate swings of ±10% in daily loads and more than that in parts mix percentages. That kind of performance is needed if the takt times calculated from final assembly rates are to be meaningful. If machines or cells are assigned families of parts, it is easier to accomodate wider swings in part mixes.

There's more to uniform load scheduling than creating a mixed model assembly schedule and a disciplined pull system. If affects all processes, including order entry. One does not encourage sales by offering large lots at a big discount — not without careful planning so that the volume surge does not create waste. Rather, one offers everyday low prices, pointing out that the average cost over time is lower than if demand surges and dies using promotions, that is, having a uniform load schedule interacts with the marketing strategy and customer order flow process of a company.

The paradox is that a company with a uniform load schedule may be more responsive to customers. Many are. For example, 3M in making video cassettes for many years allowed 20% or so of each day's schedule to actually make phone-in orders not filled from stock. As long as the load was relatively uniform, the process easily accommodated major mix changes.

Suppliers

As a company develops its JIT capability, it soon becomes apparent that suppliers simply are part of the fabrication process not owned by the company. One would like to extend the system to them.

Partnerships with suppliers have many more considerations than JIT production, for example, participation in product design. However, one reason for limiting the number of suppliers is that it is preferable to give a supplier a uniform load covering a family of parts, just as is true of a work center in one's own shop. Where that becomes an obvious advantage, the partnership is worth seeking, and the value added by the partnership is more than just the supply of the parts. It's the flexibility of response.

To be a JIT supplier, a company must either develop its own people for JIT, or the customer must assist them. A few large companies develop suppliers. It's in their best interest, even if the suppliers also serve competitors. By so doing they are assured of having highly competent suppliers, at least in production.

References

Greif, M. *The Visual Factory*, Productivity Press, Portland, OR, 1991. Basic. Many pictures.

Hall, R. W. *Attaining Manufacturing Excellence*, Irwin-McGraw-Hill, Homewood, IL, 1987. An overview explaining the why's of JIT.

Hirano, H. *JIT Implementation Manual*, Productivity Press, Portland, OR, 1990. Expensive, but comprehensive and detailed. Includes analysis forms.

Ohno, T. *Toyota Production System*, Productivity Press, Portland, OR, 1988. How it began. Origin of the system by the Father of JIT.

Shingo, S. *The SMED System*, Productivity Press, Portland, OR, 1985. Reducing setup times. Loaded with how-to.

Shingo, S. *A Study of the Toyota Production System*, Productivity Press, Portland OR, 1989. A classic. Earlier version was the first book on JIT in English.

13.14 Lean Manufacturing

Kwasi Amoako-Gyampah

Increasing global competition is forcing companies to seek better and better ways of competing through manufacturing. Increasing global competition is also forcing companies to redefine how they compete. Whereas in the past companies could be successful by emphasizing either low-cost production, higher quality, delivery dependability, or higher flexibility, it has becoming increasing important for companies now to develop competencies in all four areas and to be able to compete in all areas. One approach to competing that has been used successfully by the firms in Japan and has found some acceptance in the United States (at least among automobile manufacturers) is lean manufacturing.

Lean manufacturing was developed as an alternative to traditional mass production. Mass production is based on producing large volumes of limited items at low cost in an environment where workers perform minute task in repetitive fashions and a separation of powers exists between management and labor. On the other hand, lean manufacturing is aimed at producing large varieties of high-quality items very quickly in a flexible and continuously learning organization with multiskilled workers at all levels of the organization.

Lean manufacturing is a system of manufacturing that seeks to achieve more with less resources. It is a manufacturing approach that focuses on total quality management, just-in-time production, waste elimination, continuous improvement, multifunctional teams, product design, and supplier partnerships. Lean manufacturing does not only focus on core production activities, but it is also aimed at product development, component procurement, and product distribution [Karlsson and Ahlstrom, 1996]. The ultimate goal of lean manufacturing is increased productivity, lower costs, increased quality of products, shortened lead times, faster and reliable delivery of products, and enhanced flexibility.

Although the tenets of lean production were developed by the Toyota Motor Corporation in the 1950s, the term "lean production" was actually coined by a researcher involved in the International Motor Vehicle Program at the Massachusetts Institute of Technology. The results of that program was published in the book *The Machine that Changed the World* [Womack et al., 1990] and this book has been largely credited with the development of the knowledge base on lean manufacturing.

Elements of Lean Manufacturing

This section examines the various elements of lean manufacturing as mentioned in the previous section. These descriptions are not in any order of importance since all the elements are necessary for the full implementation of lean manufacturing.

Total Quality Management

Lean manufacturing requires the adoption of total quality management (TQM) principles. Some aspects of TQM such as continuous improvement and employee empowerment will be discussed later. One aspect of TQM important in lean manufacturing is focus on the customer. Focus on the customer means that **value** has to be defined from the customer's perspective. By defining value as the features that a customer desires in a product that will be offered at the right time and at the right price, the company can then focus on eliminating the non value-adding items, that is, focus on **waste** elimination.

Another TQM element necessary for lean manufacturing is measurement. This implies the use of scientific measurement tools to reduce variability in product outcomes and to improve the quality of the products. Workers will be expected to be trained in the use of statistical quality control techniques in order to able to identify and solve quality-related problems so as to enhance value to the customer. In a lean manufacturing environment, workers will be empowered to stop production processes if they detect quality problems. The producers of a part are responsible for the ultimate quality of the part.

Just-in-Time Production

The implementation of lean manufacturing requires the use of just-in-time production (JIT) and delivery. JIT is described in greater detail elsewhere in this handbook. Briefly, JIT uses **pull manufacturing** to produce only the needed materials in the smallest quantities possible and at the latest possible time for onward delivery to the customer. Materials are pulled through the value-adding chain as opposed to the traditional **push manufacturing** where materials are pushed through the value-adding chain using preset lot sizes.

The production of goods in small lot sizes requires the reduction in setup or changeover times. Traditionally, the changeover time refers to the time required to change dies. If changeover times between batches are small, then companies do not have to produce large batches at a time in order to be cost competitive. Small batch production means an ability to respond faster to changing customer demands for the existing mix of products, reduction in inventory, and therefore less space requirements, and quality problems become more visible.

contracts that the assemblers offer those suppliers. The lower tiers on the other hand will make their location decisions mostly based on cost because they typically will be supplying low–value-added parts.

Suppliers in a lean manufacturing environment are expected to make frequent deliveries and deliver only the quantities desired, that is, delivery quantities are typically small and ideally are expected to occur daily. The delivered components will go straight from the delivery vehicles to the production floors and bypass warehouses completely. This approach means that the quality of the materials has to meet the expectations of the assembler since there is no time for inspection. The approach is also based on trust and frequent communication between the suppliers and the assemblers.

Multifunctional Teams

A critical element of lean manufacturing is the use of multifunctional teams. One should expect to find the use of multifunctional teams to increase in an organization that implements lean manufacturing. In a lean manufacturing environment, workers in a team are cross-trained to perform many different tasks. Some of these tasks might involve preventive maintenance, quality control checks, process control checks, housekeeping, setups, and other production activities.

Cross-training of workers ensures that the required workforce will be available to meet the fluctuations in demand that might result from changing customer demands for various products. Workers can be moved from low demand areas to areas where the demand has picked up. For the multifunctional teams to perform well, the employees must be empowered to set their work schedules, determine breaks, make work assignments, and sometimes even to decide on new members for the teams.

Product Design

The ability to make quick changeovers during production of goods, the ability to meet ever-changing customer requirements with regard to product features, and the ability to respond quickly and flexibly to all these demands depend also on having effective product designs. Lean manufacturing requires that design for manufacturing (DFM) be built into the product right at the design stage. DFM entails that the product can be easily manufactured, will have the right quality, be reliable, and will be easily serviced once in use. Lean manufacturing and DFM require the use of cross-disciplinary teams in product development and engineering. This requires teams of professionals who are cross-trained, possess multi-skills, and are willing to be team players. In this approach, design and manufacturing are not viewed as separate sequential activities but are as integrated synchronous activities. Complete unification of the design and manufacturing activities is not required. What is needed is effective coordination and cooperation of the team members.

Under lean manufacturing, product development also requires the input of suppliers. Suppliers are relied on more and more to develop component items and subsystems. This requires more research and development effort on the part of the suppliers since they no longer simply produce items according to the manufacturer's specifications [Klier, 1993].

What Can You Expect from Adopting Lean Manufacturing?

One of the best documented examples of the benefits that can be expected from the adoption and implementation of lean manufacturing techniques is that of NUMMI, the GM-Toyota joint venture in Fremont, CA. At this plant, the use of lean manufacturing principles led to dramatic improvements in quality, productivity, inventory reduction, and low absenteeism using essentially the same workforce and facilities that previously had developed a reputation for bad quality, low productivity, and high absenteeism in the assembly of cars [Adler, 1993]. The implementation of lean manufacturing techniques by the Frendenberg-NOK General Partnership led to production lead times being cut in half, an increase in productivity of 52%, a 78% reduction in cycle time, and a reduction of 63% in move times [Day, 1994].

The results of a survey conducted among 24 companies with sales ranging from $30 million to more than $1.5 billion that had implemented lean manufacturing techniques showed the same benefits of lower

Waste Elimination

Another element of lean manufacturing is waste elimination. Waste is anything that does not add value to the customer, from product initiation to final delivery of the product to the customer. This includes waste of overproduction, raw materials, tools, equipment, labor, space requirements, and transportation requirements. All these components are related. Producing more than what is needed will mean using raw materials earlier than needed and therefore having to order more materials to replace those consumed. Tools and equipment will have to be used when not needed because of a decision to produce more, and more space will be required to store the extra inventory because of overproduction. The extra inventory hides quality and other production-related problems and increases lead times.

Continuous Improvement

The gains that can be achieved through the other elements of lean manufacturing require the implementation of a mentality of continuous improvement in the organization. The Japanese have developed a system known as **Kaizen** to focus on continuous improvement. Continuous improvement in a lean manufacturing environment requires the efforts of everyone in the organization involved in the manufacturing process — both management and labor. For example, an increase in problem identification skills and problem solving skills and a recognition that there is always a need to improve will be necessary. The goal is to be never satisfied but to constantly strive toward perfection. Emphasis is placed on small incremental improvements.

Several forums can be used in accomplishing the goals of continuous improvement. Among these are the use of quality circles, formal employee suggestion programs, multifunctional teams, and problem-solving teams. For the continuous improvement program to be successful there have to be mechanisms for implementing suggestions, providing feedback on employee suggestions, and an effective reward system for the employees. There also has to be a mechanism for monitoring the number of improvement suggestions for a given time period, the number implemented, reasons for not implementing others, and the outcomes of those implemented.

Another element that has to be present for continuous improvement to work is that it has to be embedded in a cooperative management-labor relationship [Klier, 1993]. Since most of the suggestions for continuous improvement will come from the shop floor workers, it will not work if workers have a fear that some of them will lose their jobs as a result of productivity gains made from those suggestions. Therefore, a trust relation between management and labor has to be developed, and management has to treat labor as an asset rather than cost. That commitment from management that employees will not lose their jobs as a result of a lean manufacturing project might not be easy to keep. However, with enhanced manufacturing capabilities and competitive strength arising from the adoption of lean manufacturing, the company is likely to win more business, leading to increased job opportunities [Day, 1994].

Supplier Relationships

The role of suppliers changes in a lean manufacturing environment. Suppliers are selected right at the onset of product development. The basis for supplier selection is not the typical low-cost supplier, but rather supplier selection is based on long-term relationships that are likely to have developed from proven abilities to supply other components in the past [Womack et al., 1990]. The suppliers for a manufacturer or an assembler are usually divided into "tiers". A first-tier supplier is usually given a complete component or subsystem to produce, such as a brake system for an auto assembler. The first-tier supplier might have other suppliers known as "second tiers" who might supply components or subsystems to the first tier and so on.

The number of suppliers (first tier) used by a lean manufacturer is typically low. The total number of suppliers might be large; however, only the first-tier suppliers deal directly with the assembler/manufacturer. The first-tier suppliers, because of large volumes and also because they deliver large components or complete systems, typically will locate close to their customers. This is facilitated by the longer-term raw material changes — that production workers can suggest and implement. Thus, it is first necessary to organize production operations, management functions, and personnel for green manufacturing to facilitate the identification and development of both technical and common-sense waste minimization ideas [Dillon and Fischer, 1992].

There are several important prerequisites for this process. First, it is critical to have an accounting of inputs, wastes, and their associated costs at each point in the production process. According to 1994 EPA data, 31% of all reported source reduction actions were first identified through pollution prevention opportunity or materials balance audits [EPA, 1996]. The normal financial incentives to reduce costs can be highly efficient within such an accounting system, but the actual efficiency greatly depends on the extent to which true costs are accounted for. The pinpointing of costs, particularly tracking them back to specific production processes, and the projection of future costs are challenging [Florida and Atlas, 1997; Todd, 1994]. Second, the facility must thoroughly know the environmental laws with which it must comply now and in the foreseeable future. This includes environmental permits specifically applicable to it. The facility also must assess the legal implications of possible changes in its operations (e.g., the need for permits if certain changes are made or any restrictions on using particular chemicals).

Third, green manufacturing must be a central concern of the facility's top management [Florida and Atlas, 1997; Hunt and Auster, 1990]. This is usually helped by outside pressure (from government or environmentalists) or by the convincing demonstration of its benefits (e.g., reduced production costs) [Lawrence and Morell, 1995]. Fourth, it is typically very helpful to involve production workers in green manufacturing [Florida and Atlas, 1997; Makower, 1993]. When they are involved in the environmental implications of their activities, they often make substantial contributions, especially improvements in industrial housekeeping, internal recycling, and limited changes in production processes. According to 1994 EPA data, 42% of all reported source reduction activities were first identified through management or employee recommendations [EPA, 1996].

Fifth, green manufacturing will greatly benefit from the easy availability of technical and environmental information about cleaner technology options. Both in-house technical and environmental experts and outside consultants can be useful. It also can be desirable to involve the facility's suppliers and customers in the effort [Georg et al., 1992]. Often they can provide solutions not easily perceived by the facility involved in the actual production. Finally, setting challenging objectives and monitoring the facility's progress toward achieving them can help in creating effective green manufacturing [Florida and Atlas, 1997]. The targets may be financial (e.g., cost reduction), physical (e.g., input and/or discharge reduction), legal (e.g., lowering emissions to avoid the need for an environmental permit), and personnel (e.g., fewer injuries).

Choosing Green Manufacturing Options

Once the proper organizational approach is established, the first step in choosing options for green manufacturing is making an inventory by production operation of the inputs used (e.g., energy, raw materials, and water) and the wastes generated. These wastes include off-specification products, inputs returned to their suppliers, solid wastes, and other nonproduct outputs sent to treatment or disposal facilities or discharged into the environment. The second step is selecting the most important nonproduct outputs or waste streams to focus upon. Their relative importance could depend upon the costs involved, environmental and occupational safety impacts, legal requirements, public pressures, or a combination thereof.

The third step is generating options to reduce these nonproduct outputs at their origin. These options fall into five general categories: product changes, process changes, input changes, increased internal reuse of wastes, and better housekeeping. The fourth step is to pragmatically evaluate the options for their environmental advantage, technical feasibility, economic sufficiency, and employee acceptability. With respect to economic sufficiency, calculating the payback period is usually adequate.

This evaluation usually leads to a number of options, especially in better housekeeping and input changes, which are environmentally advantageous, easy to implement, and financially desirable. Thus, the fifth step is to rapidly implement such options. There typically are other options that take longer to evaluate but that also usually lead to a substantial number that are worth implementing.

13.15 Green Manufacturing

Mark Atlas and Richard Florida

There are many ways that industrial facilities can implement technologies and workplace practices to improve the environmental outcomes of their production processes (i.e., **green manufacturing**) and many motivations for doing so. Green manufacturing can lead to lower raw material costs (e.g., recycling wastes, rather than purchasing virgin materials), production efficiency gains (e.g., less energy and water usage), reduced environmental and occupational safety expenses (e.g., smaller regulatory compliance costs and potential liabilities), and an improved corporate image (e.g., decreasing perceived environmental impacts on the public) [Porter and van der Linde, 1995].

In general, green manufacturing involves production processes that use inputs with relatively low environmental impacts, that are highly efficient, and that generate little or no waste or pollution. Green manufacturing encompasses **source reduction** (also known as waste or pollution minimization or prevention), **recycling**, and green product design. Source reduction is broadly defined to include any actions reducing the waste initially generated. Recycling includes using or reusing wastes as ingredients in a process or as an effective substitute for a commercial product or returning the waste to the original process that generated it as a substitute for raw material feedstock. Green product design involves creating products whose design, composition, and usage minimizes their environmental impacts throughout their lifecycle.

Source reduction and recycling activities already have been widely adopted by industrial facilities. According to 1993 U.S. Environmental Protection Agency (EPA) Biennial Reporting System (BRS) data, which cover facilities that generate over 95% of the country's hazardous waste, 57% and 43% of these facilities had begun, expanded, or previously implemented source reduction and recycling, respectively. According to a 1995 survey of over 200 U.S. manufacturers, 90% of them cited source reduction and 86% cited recycling as main elements in their pollution prevention plans [Florida, 1996].

Organizing for Green Manufacturing

Green manufacturing provides many opportunities for cost reduction, meeting environmental standards, and contributing to an improved corporate image. However, finding and exploiting these opportunities frequently involve more than solving technological issues. The ten most frequently cited hazardous waste minimization actions are listed in Table 13.13.

As the data show, only a small portion of these actions involves new or modified technology. Most involve improving operating practices or controls or fairly basic ideas — such as waste segregation or

TABLE 13.13 Most Frequently Cited Hazardous Waste Minimization Actions

Percent of All Actions	Waste Minimization Action
8.9	Improved maintenance schedule, recordkeeping, or procedures
8.0	Other changes in operating practices (not involving equipment changes)
7.1	Substituted raw materials
6.5	Unspecified source reduction activity
5.1	Stopped combining hazardous and nonhazardous wastes
4.8	Modified equipment, layout, or piping
4.6	Other process modifications
4.4	Instituted better controls on operating conditions
4.1	Ensured that materials not in inventory past shelf life
4.0	Changed to aqueous cleaners

N = 81,547 waste minimization actions.

Source: Tabulations from 1989, 1991, 1993, and 1995 EPA BRS databases.

Management will have to relinquish some of the decision making to lower levels. Workers will have to be cross-trained and be prepared to work in teams. Supplier cooperation will have to be developed. An environment of continuous improvement will have to be fostered. Managers considering lean manufacturing should be prepared for difficulties and failures along the way, but the benefits of increased competitive strength should make the effort worthwhile.

Defining Terms

Kaizen: A term used to characterize the Japanese approach to continuous improvement

Pull manufacturing: A manufacturing approach in which item production at any stage of the process is dictated by the demand at the next downstream operation.

Push manufacturing: A manufacturing approach in which item production at any stage is based on predetermined batch sizes regardless of the demand for the item at the next downstream operation.

Value: A customer's subjective evaluation of a product on how a product meets his or her expectations taking into consideration the product's cost.

Waste: Anything that does not add value to the customer.

References

Adler, P. S. Time-and-motion regained, *Harv. Bus. Rev.*, 71(1): 97–108, 1993.

Bergstrom, R. Y. Toward lean success, *Production*, 107(2): 58–61, 1995.

Day, J. C. The lean-production imperative, *Ind. Week*, 243(15): 70, 1994.

Karlsson, C. and Ahlstrom, P. Assessing changes towards lean production, *Int. J. Prod. Operat. Mgt.*, 16(2): 24–42, 1996.

Klier, T. How lean manufacturing changes the way we understand manufacturing sector, *Econ. Perspec.*, 17(3): 2–10, 1993.

Shadur, M. A., Rodwell, J. J., and Bamber, G. J. Factors predicting employees' approval of lean production, *Hum. Relat.*, 48(12): 403–421, 1995.

Struebing, L. Survey finds lean production yields more than reduced costs for U.S. companies, *Qual. Progr.*, 28(11): 16–18, 1995.

Womack, J. P. and Jones, D. T. Beyond Toyota: how to root out waste and pursue perfection, *Harv. Bus. Rev.*, 74(5): 140–158, 1996.

Womack, J. P., Jones, D. T., and Roos, D. *The Machine that Changed the World*, Rawson Associates, New York, 1990.

Further Information

A good comprehensive material on lean manufacturing is the book *The Machine that Changed the World* (see reference list above). Even though it focuses on lean manufacturing in the automotive industry, the principles are applicable universally.

The paper "Beyond Toyota: How to Root Out Waste and Pursue Perfection" also by James P. Womack and Daniel T. Jones, *Harvard Business Review*, September-October, 1996, discusses important steps needed in implementing a comprehensive lean manufacturing system.

For companies interested in implementing lean manufacturing in a global supply chain environment, the article "Lean Production in an International Supply Chain" by David Levy, *Sloan Management Review*, Winter, 1997, provides valuable insights.

Managers interested in understanding how the adoption of lean manufacturing might affect the way they deal with their suppliers should read the article "The Impact of Lean Manufacturing on Sourcing Relationships" by Thomas Klier, *Economic Perspectives* [Federal Reserve Bank of Chicago], 18(4): 8-18, 1994.

costs, increased productivity, higher quality, shortened lead times, and higher inventory turnover. In addition, an increase in worker empowerment was reported by the respondents [Struebing, 1995]. Klier [1993] reports of two companies, Luk Inc. and Eaton Corp., who were able to achieve higher than average productivity gains in their operations as a result of the use of lean manufacturing techniques. These few examples demonstrate the benefits that can be obtained with the implementation of lean manufacturing.

How to Make Lean Manufacturing Successful

Even though many companies outside the automotive industry have generally accepted the principles of lean manufacturing, very few have actually taken the necessary steps to incorporate the concepts into a coherent business system [Womack and Jones, 1996]. Some executives fear that costs might increase, that the process might take too long, and that the organization might not be able to handle the change in culture required. However, it has to be emphasized that the costs for not adopting lean manufacturing can be also be tremendous.

To achieve lean manufacturing success requires long-term commitment and a recognition that there are bound to be failures and setbacks along the way. It has been estimated that moving from mass production to lean manufacturing can take at least 5 years [Bergstrom, 1995]. This might require a "champion" in the organization who will be committed to the program.

Lean manufacturing success might require that the organization be reorganized structurally. This reorganization not only has to incorporate the use of teams but also allow for the development of multiple career paths within the organization. Lean manufacturing requires an environment where workers are empowered, teamwork is encouraged, creativity is fostered, and the complete involvement of all employees is nurtured [Day, 1994]. The entire supply chain also has to be adequately managed. Whereas the quality of the products of first-tier suppliers might be adequate, the quality of items supplied by lower-tier suppliers might not and unless that is properly managed the desired results of lean manufacturing might not be achieved.

Lean manufacturing can result in increased stress. The stress results from the synchronized nature of operations, the fact that there are no built-in slacks in the operations, and the emphasis on continuous improvement whereby sometimes problems are intentionally injected into the system in order to foster improvement. However, high stress level of employees does not mean they will not accept lean manufacturing. It has been demonstrated that employees' acceptance of lean manufacturing principles is more likely to depend on their commitment to the company and their motivation [Shadur et al., 1995]. Thus, management has the responsibility to put in place the processes necessary to ensure employee commitment to the lean manufacturing program.

Summary

This section has examined some of the basic elements of lean manufacturing. Under lean manufacturing, small batches matched to customers' needs are produced just in time using teams of workers. This contrasts with traditional manufacturing where parts are produced in large volumes by workers performing only few functions with several non–value-adding stages in the process. Lean manufacturing emphasizes team work, employee empowerment, continuous improvement, and waste elimination. Lean manufacturing requires reliance on a few core suppliers to produce large proportions of a company's output. These suppliers are also very often involved in product design and development.

Companies that have implemented aspects of lean manufacturing have reported several benefits. Some of these benefits include increased worker productivity, decreased work in process, decreased move times on the plant floor, reduced cycle times, decreased worker compensation costs, reduced product introduction times, higher quality, greater employee empowerment, reduced absenteeism, and an increase in business volume.

To be successful, the top management in the organization must be committed to the lean manufacturing program, and the presence of a lean manufacturing champion in the organization will help.

Potential Green Manufacturing Options

As noted earlier, the options for green manufacturing can be divided into five major areas: product changes, production process changes, changes of inputs in the production process, internal reuse of wastes, and better housekeeping. The following discussion focuses on the physical nature of changes that can be implemented (excluding green product changes, which are discussed elsewhere).

Changes in Production Processes

Many major production process changes fall into the following categories: (1) changing dependence on human intervention, (2) use of a **continuous** instead of a **batch** process, (3) changing the nature of the steps in the production process, (4) eliminating steps in the production process, and (5) changing cleaning processes.

Production that is dependent on active human intervention has a significant failure rate. This may lead to various problems, ranging from off-specification products to major accidents. A strategy that can reduce the dependence of production processes on active human intervention is having machines take over parts of what humans used to do. Automated process control, robots used for welding purposes, and numerically controlled cutting tools all may reduce wastes.

With respect to using a continuous, rather than batch, process, the former consistently causes less environmental impact than the latter. This is due to the reduction of residuals in the production machinery and thus the decreased need for cleaning, and better opportunities for process control, allowing for improved resource and energy efficiency and reducing off-specification products. There are, however, opportunities for environmentally improved technology in batch processes. For chemical batch processes, for instance, the main waste prevention methods are (1) eliminate or minimize unwanted by-products, possibly by changing reactants, processes, or equipment, (2) recycle the solvents used in reactions and extractions, and (3) recycle excess reactants. Furthermore, careful design and well-planned use can also minimize residuals to be cleaned away when batch processes are involved.

Changing the nature of steps in a production process — whether physical, chemical, or biological — can considerably affect its environmental impact. Such changes may involve switching from one chemical process to another or from a chemical to a physical or biological process or vice versa. In general, using a more selective production route — such as through inorganic catalysts and enzymes — will be environmentally beneficial by reducing inputs and their associated wastes. Switching from a chemical to a physical production process also may be beneficial. For example, the banning of chlorofluorocarbons led to other ways of producing flexible polyurethane foams. One resulting process was based on the controlled use of variable pressure, where carbon dioxide and water blow the foam, with the size of the foam cells depending upon the pressure applied. An example of an environmentally beneficial change in the physical nature of a process is using electrodynamics in spraying. A major problem of spraying processes is that a significant amount of sprayed material misses its target. In such cases, waste may be greatly reduced by giving the target and the sprayed material opposite electrical charges.

Eliminating steps in the production process may prevent wastes because each step typically creates wastes. For example, facilities have developed processes that eliminated several painting steps. These cut costs and reduce the paint used and thus emissions and waste. In the chemical industry, there is a trend to eliminate neutralization steps that generate waste salts as by-products. This is mainly achieved by using a more selective type of synthesis.

Cleaning is the source of considerable environmental impacts from production processes. These impacts can be partly reduced by changing inputs in the cleaning process (e.g., using water-based cleaners rather than solvents). Also, production processes can be changed so that the need for cleaning is reduced or eliminated, such as in the microelectronics industry, where improved production techniques have sharply reduced the need for cleaning with organic solvents. Sometimes, by careful consideration of production sequences, the need for cleaning can be eliminated, such as in textile printing, where good planning of printing sequences may eliminate the need for cleaning away residual pigments. In other processes, reduced cleaning is achieved by minimizing carryover from one process step to the next. The switch from batch to continuous processes will also usually reduce the need for cleaning.

Changes of Inputs in the Production Process

Changes in inputs is an important tool in green manufacturing. Both major and minor product ingredients and inputs that contribute to production, without being incorporated in the end product, may be worth changing. An example where changing a minor input in production may substantially reduce its environmental impact is the use of paints in the production of cars and airplanes. The introduction of powder-based and high solids paints substantially reduces the emission of volatile organic compounds. Also, substituting water-based for solvent-based coatings may lessen environmental impacts.

Internal Reuse

The potential for internal reuse is often substantial, with many possibilities for the reuse of water, energy, and some chemicals and metals. Washing, heating, and cooling in a countercurrent process will facilitate the internal reuse of energy and water. Closed-loop process water recycling that replaces single-pass systems is usually economically attractive, with both water and chemicals potentially being recycled. In some production processes there may be possibilities for **cascade-type reuse**, in which water used in one process step is used in another process step where quality requirements are less stringent. Similarly, energy may be used in a cascade-type way where waste heat from high-temperature processes is used to meet demand for lower-temperature heat.

Better Housekeeping

Good housekeeping refers to generally simple, routinized, nonresource-intensive measures that keep a facility in good working and environmental order. It includes segregating wastes, minimizing chemical and waste inventories, installing overflow alarms and automatic shutoff valves, eliminating leaks and drips, placing collecting devices where spills may occur, frequent inspections aimed at identifying environmental concerns and potential malfunctionings of the production process, instituting better controls on operating conditions (e.g., flow rate, temperature, and pressure), regular fine tuning of machinery, and optimizing maintenance schedules. These types of actions often offer relatively quick, easy, and inexpensive ways to reduce chemical use and wastes.

Defining Terms

Batch process: A process that is not in continuous or mass production and in which operations are carried out with discrete quantities of material or a limited number of items.

Cascade-type reuse: Input used in one process step is used in another process step where quality requirements are less stringent.

Continuous process: A process that operates on a continuous flow (e.g., materials or time) basis, in contrast to batch, intermittent, or sequential operations.

Green manufacturing: Production processes that use inputs with relatively low environmental impacts, that are highly efficient, and that generate little or no waste or pollution.

Recycling: Using or reusing wastes as ingredients in a process or as an effective substitute for a commercial product or returning the waste to the original process that generated it as a substitute for raw material feedstock.

Source reduction: Any actions reducing the waste initially generated.

References

Dillon, P. and Fischer, K. *Environmental Management in Corporations: Methods and Motivations,* Tufts University Press, Medford, MA, 1992.

Florida, R. Lean and green: the move to environmentally conscious manufacturing, *Cal. Mgt. Rev.,* 39: 80–105, 1996.

Florida, R. and Atlas, M. *Report of Field Research on Environmentally-Conscious Manufacturing in the United States,* Carnegie Mellon University, Pittsburgh, PA, 1997.

Georg, S., Ropke, I., and Jorgensen, U. Clean technology — innovation and environmental regulation, *Environ. Resource Econ.* 2: 533–550, 1992.

Hunt, C. and Auster, E. Proactive environmental management: avoiding the toxic trap, *Sloan Mgt. Rev.*, Winter: 7–18, 1990.

Lawrence, A. and Morell, D. Leading-edge environmental management: motivation, opportunity, resources, and process, In *Research in Corporate Social Performance and Policy, Supplement 1*, J. Post, D. Collins, and M. Starik, eds., pp. 99–126, JAI Press, Greenwich, CT, 1995.

Makower, J. *The e Factor: The Bottom-Line Approach to Environmentally Responsible Business*, Times Books, New York, 1993.

Porter, M. E. and van der Linde, C. Green and competitive: ending the stalemate, *Harvard Bus. Rev.*, 73: 120–134, 1995.

Todd, R. Zero-loss environmental accounting systems, In *The Greening of Industrial Ecosystems*, B. Allenby and D. Richards, ed., pp. 191–200, National Academy Press, Washington, DC, 1994.

U.S. Environmental Protection Agency. *1994 Toxics Release Inventory Public Data Release*, Office of Pollution Prevention and Toxics, Washington, DC, 1996.

Further Information

The Academy of Management has an Organizations and the Natural Environment section for members interested in the organizational management aspects of green manufacturing. For membership forms, contact The Academy of Management Business Office, Pace University, P.O. Box 3020, Briarcliff Manor, NY 10510-8020; phone (914) 923-2607. Also, many of the Web sites cited below lead to other organizations with particular interests in green manufacturing.

The quarterly *Journal of Industrial Ecology* provides research and case studies concerning green manufacturing. For subscription information, contact MIT Press Journals, 55 Hayward Street, Cambridge, MA 02142; phone (617) 253-2889.

There are numerous Web sites with green manufacturing-related information, including the following: http://www.epa.gov/epaoswer/non-hw/reduce/wstewise/index.htm; http://es.inel.gov/; http://www.epa.gov/greenlights.html; http://www.hazard.uiuc.edu/wmrc/greatl/clearinghouse.html; and http://www.turi.org/P2GEMS/.