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# Applying Modern Manufacturing Processes to Engineering Prototypes


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## INTRODUCTION

### Why Study Prototype Processes?

Today's global economy has reached a scale that no one could have imagined possible just a few decades ago. Perhaps the most obvious result of this world-scale economy has been the expanded customer base for consumer goods and services. However, a broader consumer base has brought with it more stringent customer requirements for goods and services. A customer's ability to obtain goods and services from any number of competing companies both at home and abroad make it imperative that suppliers of these products perform flawlessly the first time and every time. Consumer expectations for quality have assumed all-time highs. The current paradigm insists that world-class quality be no more expensive today than mediocre quality was in days past. Given this environment, manufacturers attempting to peddle goods viewed by consumers as having sub-standard quality or a price tag that is too high are likely to find those goods sitting in their inventories while competitors gain market share. Disney's Michael Eisner has been quoted as saying what brings managers down isn't "the lack of understanding some arithmetic table, not the lack of understanding what the information highway is, but the lack of understanding why somebody is unhappy." (Jennings & Haughton, 2002, 240). In the context of meeting market expectations, Eisner's "lack of understanding" is certainly applicable to companies failing to ascertain what their customers want and to work toward providing it each and every time. The sad lesson being learned by more and more companies is that an unsatisfied customer will remain so only as long as it takes to find a new supplier.

Exhaustive research has been focused on ways in which companies can improve the quality of their goods while at the same time reducing both the cost and time required to produce them. Companies have implemented improvement methodologies to identify and eliminate waste from their processes, to increase the speed of production, to identify and correct defects at their point of origin, and to find less expensive materials from which to fabricate their products. However, one item that is often missing from mainline production improvement programs is that of introducing new products to market in a timely manner. In a fiercely competitive marketplace companies are often faced with two choices: either be the leader into a new product market or follow the leader and be faced with playing catch-up to gain acceptable market share. Success, then, lies in a company's ability to perform the following tasks:

- identify a consumer need (or want)
- design a product to fill that need
- produce an engineering prototype of the new product for test and evaluation
- if acceptable produce the new product for distribution to meet the consumer need, and
- do all these things before its competitor(s).

Even mature companies securely entrenched in their markets must continually strive to meet consumer expectations for products that are newer, better, stronger, lighter, more fuel efficient, more environmentally friendly . . . and the list goes on. Companies trying to avoid being overrun by their competition focus tremendous effort on bringing new products to market faster than ever before.

In the earliest stages of introducing a new product, modern computer assisted design (CAD) applications allow engineering research and development to proceed at an amazing pace. Design changes can be made and distributed electronically for approval from an engineer's desktop in a fraction of the time it would have taken to route paper copies just a few years ago. Modeling software allows designers to view graphical representations (both stationary and in motion) before any materials are purchased or production assets are committed. At this stage design changes can still be made at a relatively small cost. After a successful product launch, modern materials management and manufacturing tools have been developed to speed the production and distribution of new products. But somewhere between what has traditionally been labeled product design and the release of a product to manufacturing lies the often overlooked phase of producing engineering prototypes. Prototypes are essentially just models of products or services that allow designers to verify their intended functionality. If prototype evaluation demonstrates acceptability, the prototype then becomes the basis for production items. In reality the development and production of prototypes are still a part of the design stage of product development. Bedworth, Henderson, and Wolfe (1991) point out that "as much as 70% of the production costs of a manufactured part are determined during the engineering design process . . . therefore, only 30% of the part's cost is subject to money-saving efforts during the manufacturing planning stage." (p. 72). It has also been estimated that as much as 70 to 80 percent of a product's total lifecycle cost is determined during its design cycle (Schaeffer, 2002, 13). With so much cost being predetermined before a product ever makes it into production, it is of vital importance that every aspect of the design cycle be examined for improvement opportunities. The design phase of new product introduction has been described as an "iterative process consisting of six phases:

1) Recognition of need
2) Definition of problem
3) Synthesis
4) Analysis and optimization
5) Evaluation
6) Presentation" (Bedworth et al., 1991, 75).

Of these six steps, the evaluation phase is the first to engage personnel beyond the design engineer(s). During this phase engineering prototypes are fabricated to allow designers to test their theories under real-world conditions and revise design parameters found to be inadequate. Thus, fabricating and testing engineering prototypes are a part of the product lifecycle where the most significant gains can be made in cost reduction. This coupled with the ability to make quality improvements at such an early stage of product development make the prototype phase an ideal place to focus improvement efforts.

Of necessity, prototype production involves material procurement and some level of assembly and test effort. This stage of design bears striking similarities to full-scale production operations. The purpose, then, for this course is to examine these similarities and determine if they share enough common ground to allow the exchange of tools and practices between them to help relieve the 70% to 80% cost burden described above.

**What will be Studied?**

Increasing competition in the marketplace has forced companies to make real, substantive changes in the way they operate. The goal sought by today's industrial leaders is world-class performance. Schonberger (1986) asserts that the main goal of world-class manufacturing can be summed up in the words of the Olympic Games motto: "*Citius*, *altius*, *fortius*. From the Latin the English translation is 'faster, higher, stronger.' The world-class manufacturing equivalent is *continual and rapid improvement*." (p. 2). He further emphasizes the importance of

> a full range of elements of production . . . management of quality, job classification, labor relations, training, staff support, sourcing, supplier and customer relations, product design, plant organization, scheduling, inventory management, transport, handling, equipment selection, equipment maintenance, the product line, the accounting system, the role of the computer, automation, and others. (p. 1).

New products face an uphill climb to world-class success on their journey from initial design concept all the way through to end item delivery to customers. To ensure success of new products, every phase of their development must be scrutinized to identify potential areas of improvement. Waste must be identified and eliminated (in both materials and labor) to improve profit margins and delivery times. Processes must be fine-tuned to achieve throughput targets. In recent years, extensive research has gone into developing process improvement methodologies to assist companies with their improvements. Computer-Aided Design (CAD) systems have been developed to assist designers with converting product ideas to reality, thus, greatly reducing the time between when a new product idea is conceived and when it actually enters production. Many successful firms have adopted concurrent engineering practices as a means to allow time-critical design functions to be carried out simultaneously. Equally important are tools that have been developed to help companies improve their methods of manufacturing new products. Resource planning tools give managers and planners the ability to review production requirements (including human resources, materials, equipment, facilities, etc.) and to plan the most efficient use of each resource. And for the post-production phase of a product's lifecycle, improvements have been developed for finished goods inventory and distribution to ensure that the products make it into the hands of consumers with the least amount of delay and cost.

Development of these improvement methodologies and tools have resulted in drastic reductions in time to market, quality improvement rates never before imagined, and cost reductions once thought unachievable. However, one area of largely untapped improvement potential is that of producing engineering prototypes. Once a new design has reached a reasonable level of stability it is desirable to have prototype models fabricated for test and evaluation prior to releasing the product into the manufacturing cycle. Generally a small number of prototypes are produced and subjected to various levels of inspection to determine, first, that the design concept has been accurately captured and, second, that the samples are functionally acceptable. This phase of new product development is iterative in nature. Flaws detected in prototype units are corrected, sometimes new features are added, new prototypes ordered, and the testing begins again. This process continues until engineering is satisfied with the results and releases the design to manufacturing. This course explores process improvement opportunities applicable to prototype development and production. Emphasis is placed on identifying those tools originally designed for other areas of production that may be appropriate for transfer to the engineering prototype phase.

## Scope of the Study

The latter part of the 20th century saw an intense interest among the manufacturing community in achieving World-Class Manufacturing status. The process of introducing new products to the marketplace was scrutinized from every conceivable angle to identify improvement opportunities. Benchmarking partners teamed up to identify best-in-class methods to be emulated in their own improvement efforts. The results were leaner, more agile, companies ready to face the competitive challenges of 21st century markets. The methodologies that have led companies to success in developing, manufacturing, and marketing new products in recent years have been amply documented. Tools have been developed to assist engineering with upfront research and development processes. Tools have also been developed to assist factory planners, managers, and engineers with the design and operation of manufacturing processes. Tools have been devised to assist with supply chain management. And still more tools have been developed to aid in raw material and finished goods inventory and tracking.

This course examines many of the tools that have been most successfully developed for these areas to determine their applicability to the engineering prototype phase of new product introduction. The production of engineering prototypes shares similar processes with other areas of the overall manufacturing cycle. In effect, engineering prototype production is a microcosm of the greater product manufacturing cycle yet has been largely neglected in terms of process improvement strategies. Yet, the similarities between prototype production and full-blown factory production will provide a framework of comparison for this course.

## Glossary

Following is a list of terms used throughout the course as defined in a manufacturing context.

**Approved Parts List (APL):** The APL is a list of components approved for use in the manufacture of a company's sellable merchandise. Approval is generally based upon a series of qualifying activities including, but not limited to:

- Review of a supplier's manufacturing capabilities, quality management processes, and cost structure
- Evaluation of a part's ability to function as designed and advertised, in the intended application, and under the expected worst-case operating conditions
- Verification of a part's compatibility with a company's current and expected manufacturing processes.

**Benchmarking:** The process of "identifying, understanding, and adapting outstanding practices from others, in order to improve your own performance." (O'Dell & Grayson, 2000, p.2).

**Computer-Aided Design (CAD):** A design process that "involves the use of computers in creating or modifying the product design" (Amrine, Ritchey, Moodie, & Kmec, 1993, p. 119). The term is used interchangeably to refer to both the process and the software used.

**Data:** "Raw facts about the organization and its business transactions." (Whitten & Bentley, 1998, p.37). More often than not, data by itself has little meaning.

**Design:** "All activities which transform a collection of inputs into a product satisfying a need." (Bedworth, Henderson, & Wolfe, 1991, p.134).

**Information:** "Data that has been refined and organized by processing and purposeful intelligence." (Whitten & Bentley, 1998, p.38).

**Just-in-Time Manufacturing:** A manufacturing philosophy focused on providing a work center with its required resources (manpower, material, equipment, etc.) when it needs them and not before.

**Lead-Time:** A period of time spent waiting for an outcome of one process prior to the start of another. For example, when a component part is procured the time between the decision to make the purchase and the actual delivery of the part is know as the procurement lead-time.

**Lean Manufacturing:** A manufacturing philosophy that focuses on identifying waste in every manufacturing process and systematically removing that waste. A major focus is made on removing "wait" times associated with production and creating an environment where all process time is actual "hands on" time.

**Material Requirements Planning (MRP):** A computer-based information system developed to handle scheduling and ordering materials needed for production. An MRP system is designed to convert a production plan for a specific number of assemblies into purchasing requirements for components and/or raw materials by working backwards from the actual due date and taking into account individual material lead-times.

**Manufacturing Resources Planning (MRP II):** MRP II can be thought of as a second generation MRP system that goes beyond materials planning to include business planning, production planning, and incorporate the master production schedule of a factory.

**Operations Management:** "The management of systems or processes that create goods and/or provide services." (Stevenson, 1999, p.4).

**Reengineering:** A "planned redesign of all or part of a process" (AT&T, 1991, p. v) intended to bring about order of magnitude improvements in the process.

**Theory of Constraints (TOC):** An operation philosophy that focuses on identifying and eliminating the bottlenecks in a process. Bottlenecks are the constraining items in a production system. The theory holds that removing the worst constraint in the system will cause another constraint to surface as the worst. Repeating the process continually improves product flow in a factory.

**Total Quality Management (TQM):** A quality improvement methodology stressing the need to continuously improve every aspect of a business process in order to effect greater customer satisfaction.

**Work-in-Process (WIP):** A measure of the amount of material that has left raw material stock but has not yet become finished goods. (Dewar, 2001, p. 5).

**World-Class Manufacturing:** This is a term generally used to describe the best possible manufacturing techniques when a company compares itself to any manufacturing industry in the world.

## HISTORICAL BACKGROUND

A full appreciation of the importance of streamlining the New Product Introduction process, particularly the engineering prototype portion, requires an understanding of the modern manufacturing environment and the requirements it places on every aspect of a product's life cycle. Today's American factory environment owes much to techniques borrowed from Japan's post-World War II industrial complex. A growing American trade deficit beginning in the seventies and continuing even to the present provided the impetus for examining what foreign competitors were doing better and faster than American industries themselves. Increasingly, during these decades of study, Japanese factories became the focus of intense scrutiny by investigators seeking to unlock the keys to their success. As the results of these studies were published, American managers began to emulate what were deemed the best Japanese practices in an effort to regain lost market share.

In today's global economy, these borrowed techniques are undergoing constant review and revision to ensure that every possible competitive advantage can be achieved. The following section provides a study of some of tools that have been developed in response to these decades of study and have been successful in reshaping the modern manufacturing landscape. These tools, although generally developed to exploit the full potential of a production operation, will be demonstrated to have similar applicability to the production of engineering prototypes in support of new production introduction.

## REVIEW OF THE TOOLS

Following is a review of some specific tools and techniques that have been developed in efforts to make modern manufacturing operations the very best they can be. Obviously an examination of every tool's development and success would far exceed the scope of this course. Instead a representative subset of the tools will be presented along with their native manufacturing setting as the frame of reference. Then each tool will be evaluated for it's suitability for use in the production of engineering prototypes. Appendix A provides a more detailed view of the tools in tabulated form for further reference.

### Quality Circle

One of the earliest tools to be successfully borrowed from Japanese industry was the Quality Circle. It appeared with different names among American companies (Quality Circle, QC Circle, Q circle, etc.), but whatever the nomenclature its main premise was that "quality can be improved through the participation of employees in the solving of quality problems." (Amrine et al., 1993, p. 411). Quality Circles were generally comprised of small groups of employees from the same department who met once a week to discuss quality problems, determine their causes, and recommend corrective action. Some companies granted the employee groups autonomy to initiate corrective action on their own. Quality Circles had two notable characteristics that enabled their success. First, small group sizes (ranging from as few as three to as many as 25 members) made them more nimble and made it easier to reach consensus during short meetings. Second, all group members were volunteers, meaning those in attendance wanted to be present and to participate in product improvements. Although most Quality Circles were made up of employees from a single work group, they could invite workers from other areas to participate if necessary to broaden the expertise of the team. Judged against such goals as improving product quality, increasing productivity, and motivating the workforce, the Quality Circles have to be considered a success. Their ability to get line workers involved in the process of identifying and improving product quality was an important stepping stone on the road to quality improvement in America. Indeed, creating an environment where employees felt that their expertise was valued was a key to most of quality initiatives that would follow. Retired U.S. Navy Capt. Michael Abrashoff (2002) conducted an exit poll of enlisted personnel leaving the Navy and from his sampling found the following top four reasons why they chose to leave rather than pursue a naval career:

1) They weren't treated with respect or dignity.
2) They were prevented from making an impact on the organization.
3) They weren't listened to.
4) They weren't rewarded with more responsibility.

These same reasons had been at the root of employee discontent in American factories for decades and were likely contributing factors to unacceptable levels of quality. Thus Quality Circles gave many employees the opportunities they had long desired: to be able to share their knowledge and experience and to bring about meaningful changes.

Used less frequently now than in years past, this tool still provides a solid method of allowing workers involved in either the same or similar operations to suggest improvement methods based on their collective knowledge and experience. These group meetings are comprised of volunteers who meet periodically (once a week is common) to discuss quality problems in their areas of influence and to devise improvement methods. The key strengths provided by these groups are, first, that individuals closest to production problems become involved with solving the problems and, second, allowing workers to be a part of problem resolution fosters a greater sense of self-worth.

The basic application of quality circle concepts to released-item production is relatively simple. Full-scale assembly generally involves multiple workers performing similar operations. Gathering a team of these workers allows a comparison of multiple viewpoints of the same operations. This provides for dialogue to discuss multiple solutions to perceived problems. Prototype assembly, on the other hand, is generally carried out by one or a few workers performing a wide range of dissimilar operations. A basic scenario begins with design engineer creating a preliminary schematic or assembly sketch of a product and delivering it to an assembler. The assembler gathers the raw materials (or components) necessary to assemble the prototype. These materials may be procured by the engineer, the assembler, or by someone designated to manage an engineering materials stockroom. Once the materials are available, the prototype is assembled and tested as prescribed by engineering. Prototype testing may be performed by the design engineer, the assembler, dedicated test personnel, etc. The important point to note is that generally, a very small group of individuals with diverse talents and job descriptions comprise the entire production team. Quality circle types of activities in this environment are required to focus on a broader scope than those in a typical production manufacturing environment. Rather than focusing on a single operation or set of operations, each team member needs to look at the "big picture" to identify areas of improvement. Rather than focusing on quality defects in *products* that can be corrected, quality circles at the prototype level will get better results by focusing on defects in *processes* and how to improve the overall prototype process to improve speed and reduce costs.

**Just-in-Time (JIT)**

Two of the most important goals of the JIT manufacturing philosophy were reductions in inventory and response time. To succeed in reducing raw material inventories, companies were forced to share planning data with their suppliers. Under JIT guidelines, purchasing decisions were no longer driven by economical order quantities, but instead by how many of each item was required to meet factory demand for a specific time period. These periods varied depending upon the industry, the availability of the materials in question, and the amount of risk deemed acceptable by management. If materials were available locally, purchase orders might specify that deliveries be made several times a day to alleviate the need for raw material handling and storage prior to its use. Materials shipped in from long distances, on the other hand, might be purchased in slightly larger quantities to prevent work stoppages in the event of transportation difficulties. But the goal was always to keep minimal raw material stock on hand. Note that the ideal situation, as the name implies, was for materials to arrive at each work station just in time for their use – not before and certainly not after. According to Schonberger (1982) "the JIT ideal is for all materials to be in active use as elements of work in process, never at rest collecting carrying charges." (p. 16). As mentioned earlier, information sharing was a vital key to the success of JIT operations. Suppliers were accustomed to receiving purchase orders for large "economical" quantities with the assumption that all parts were needed as soon as possible. Under JIT, purchase orders for smaller quantities were placed along with dates when the parts were actually required for production. This allowed suppliers to tailor their own manufacturing processes to support "real" demand instead of just providing their customers with inventory. Resources could be diverted from producing materials that wouldn't be needed for another month to producing critical items needed the following week, if necessary, to prevent a customer's assembly lines from shutting down. Shared schedule information also allowed suppliers to identify items that could not be provided within the timeframe required by their customers and either offer suggested alternate materials or turn down orders.

Reducing finished goods inventories required changing the manufacturing strategy to one of producing only what was needed to fill customer orders in any given time period. Further production beyond what was needed was recognized as a waste of labor and materials and not allowed. To succeed, manufacturing processes had to be changed from the traditional "push" system to a "pull" system. Under the traditional manufacturing push plan, a production schedule called for a predetermined output quantity from an assembly line. Each assembly operation was designed to produce its output based on optimized assembly techniques with an optimum output quantity. The standard output quantity was determined by optimizing the operation itself with little or no thought given to the other operations within the assembly line. Thus, it was possible for one operation to produce more widgets than the following operation could handle – resulting in an inflated buffer stock between operations. Figure 1 shows a graphical representation of the push system.

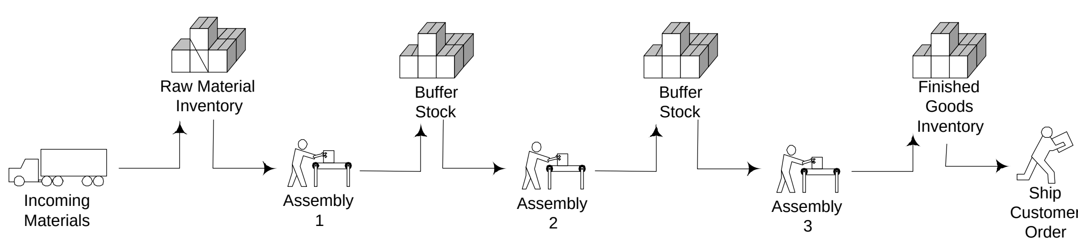


**Figure 1: Traditional Push-Type Manufacturing Process**

The pull system introduced for JIT operations basically took the opposite approach. Assembly processes were designed to produce only what was needed to meet customer demand. Ideally, if no customer orders were pending, no production took place. Again, ideally, when a customer order was placed, a production order would be initiated to produce the amount of product needed to fill the order. In order to accomplish this without producing unnecessary buffer stock, the shipping department would request what it needed to fill the order from the final assembly operation, which would in turn request what it needed from its predecessor operation. This would continue until the first assembly operation requested what it needed from raw material stock. With careful planning and effective communications with suppliers, a just-in-time delivery system as described above could be established to support the pull-type assembly process. Once raw materials were delivered, they would be processed by the first assembly operation (only enough to fill the requirements of the next operation) and passed on to the next operation. The process would continue with each successive operation producing only what had been requested by the next operation until the finished product was available to fill the customer order. By producing only enough to meet demand, finished goods inventory levels could be minimized. Again, note that this was the ideal process flow. In actuality some operations would, by virtue of their process, need to produce more than what was requested by their successor operations, thus producing some quantity of buffer stock. This was, however, kept to a minimum. Figure 2 presents a graphical representation of an ideal pull-type assembly process without buffer stocks.

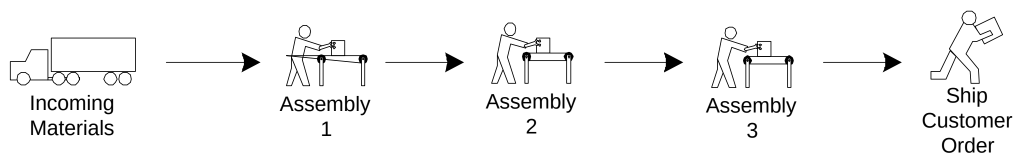


**Figure 2: JIT Pull-Type Manufacturing Process**

To reduce work order response time, sometimes referred to as cycle time, required the development of several processes. Among them were setup time reduction and work order lot size reduction. Reducing the setup times required between production operations resulted in shorter overall work order completion times. Often, multiple work centers once dedicated to a single assembly stage due to excessive setup times were replaced by single multi-tasking work centers designed for quicker setups. Time gained by speeding up the setup process could be used for additional production, employee training, general cleanup, machine maintenance, or any way management chose. Space gained by combining work centers could be reallocated for new business opportunities.

Admittedly, much of what JIT practices have to offer are of little value to prototype production. While full-scale production operations lend themselves to relatively accurate forecasting, prototype production tends to be more spurious in nature with little or no warning of upcoming material demands. During the early stages of product development designers may only be able to provide sketchy details about material requirements. Exact specifications may become available too late to order raw materials within normal factory lead-times. The resulting "eleventh hour" scramble to order parts can easily lead to missed deadlines at a point when time is of the essence. To hedge their bets, companies are forced to procure and hold basic staples of engineering materials to support prototype builds with safety stock levels based more on a *just-in-case* business plan than on the *just-in-time* model. But although inventories are often viewed as evil; in the case of prototype production, they are also a necessary evil. An R&D Management presentation developed by the Henry C. Company (2002) presents the following points to consider when establishing an R&D (and thus prototype) inventory policy:

1. Low % cost of components and materials (as compared to overall costs): 15% in R&D versus 85-95% in typical manufacturing environment.
2. Lead-time of nonstandard components is long and uncertain.
3. The R&D cycle is not finished until the last product component is assembled and successfully tested.
4. Cost of waiting for the last component can easily exceed the component cost by a factor of 100, 1000, or more! (p. 39).

The same study suggests the following inventory policy for maintaining R&D materials (including those to support engineering prototype production).

| | |
|---|---|
| 1. | Maintain in stock all inexpensive, frequently used standard components. An R&D project should never have to wait for such components. |
| 2. | Keep a reasonable, minimum amount of more expensive, but "moving", non-obsolescent components in stock. Adjust the quantity to keep the holding cost low, but monitor the stock to ensure that no shortage of such components occurs. |
| 3. | Order as soon as practicable all state-of-the-art components and any other component with uncertain delivery time. |
| 4. | Periodically dispose of all stock that is not moving or is "dead". |

**Table 1: R&D Inventory Policy** (Henry C. Company, 2002, p. 40)

One tool utilized by JIT proponents for production operations that can assist prototype operations is the *kanban* (or two bin) system of inventory replenishment. This works by dividing engineering parts into two identical bins and pulling parts as needed from only one bin at a time. Stock depletion of the materials in the first bin becomes the trigger for reordering. Parts are then taken from the second bin to meet demand requirements while new parts are being procured. When ordered parts arrive they are placed in the empty bin to become the backup supply during the next reorder cycle. Using this kind of visual reorder stimulus frees up workers who might otherwise have to continually monitor inventory levels. In some cases, vendor replenishment may be utilized to replenish the stock by having vendor representatives visit the inventory area periodically and refill empty *kanban* containers.

The smaller lot sizes that JIT practices dictate in modern factory environments are a natural part of the prototype world. Since the purpose of prototypes is to verify design concepts, build quantities are intentionally kept small to avoid producing excessive amounts of unusable assemblies if the design proves inadequate. Therefore JIT practices offer little to improve this portion of the prototype effort.

Reducing setup time is an important part of the JIT philosophy that can be applied equally well to factory production or to engineering prototypes. It is not unusual for numerous prototypes to be fabricated by the same workers using shared, general-purpose equipment. The ability of workers to quickly change setups (including tooling, machine heads, fixturing, cutting dies, injection molds, solder paste stencils, etc.) can shave time from the assembly process. The time thus saved can be applied to design verification and/or redesign if the original concept fails to perform as expected.

## Material Requirements Planning (MRP)

Perhaps the most important contribution made by MRP systems was the organization they added to manufacturing operations. Before MRP systems could plan the materials needed for manufacture, engineering had to break a product down into its individual building blocks. The individual blocks then had to be related to one another in a product structure that showed which raw materials would be used to produce sub-assemblies and which sub-assemblies would be combined with additional raw materials or sub-assemblies to make higher level subassemblies or finished products. Once the product structure was developed and converted to bills of material (BOMs) these could be combined with a master production schedule to provide the necessary inputs to the MRP system. With these inputs, the system could calculate which materials to buy, how many were required, and precisely when they should be delivered to meet a prescribed production schedule. Once the BOM information is collected and loaded into the MRP software, a vast array of computations for scheduling purchases or performing "what-if" analyses given different production output scenarios become possible. Lack of accurate product structure information can result in serious consequences to a company's bottom line. Clancy (1997) warns that

> producing product with a wrong component in an engineering BOM . . . can negatively impact your company's performance through
>
> - Incorrect costing of product,
> - Inaccurate inventory levels,
> - Accounting variances,
> - Customer returns,
> - Production of out-of-spec units,
> - Potential product liability claims. (p. 1).

For example, incorrect part quantities can lead to either a shortage of parts causing time delays or too many parts ordered driving material costs too high. Incorrect manufacturer's part numbers (MPN's) can lead to delays while supply chain personnel attempt to locate stocks of non-existent materials or can lead to installation of an incorrect part resulting in test delays. Chow and McElroy (2002) note that while the basic format for defining an item's product structure in a BOM has remained the same for decades, still "routinely, 40 to 80 percent arrive at manufacturing with problems, and resolution of the issues can add days or even weeks to new product introduction timeframes and increase costs." (p. 26). Poor BOM management can result in any of the following:

- Management has limited visibility into product costs during the development phase, when those costs can still be reduced.
- The design team has no way to fully collaborate with the supply chain or even with one another.
- The institution retains little of the knowledge assembled during a product's development because it has no way to organize the information and no place to store it.
- The inefficient, cumbersome process of compiling BOM information to hand off from engineering to manufacturing dramatically slows a product's time to market. (OpenSpec, 2002, p. 3).

MRP systems are often not utilized at the engineering prototype stage of product development. Perhaps the most common reason is that MRP capabilities generally reside at the manufacturing operations level of the corporate structure and engineering prototypes are more often produced under design engineering direction. A secondary reason for lack of MRP support is that prototypes are generally produced in small numbers with heavy demand for quick turn-around. MRP systems are designed to facilitate material procurement within standard lead-times and prototype development often must be completed long before standard delivery lead-times will allow.

Due to these constraints MRP *per se* does not lend itself well to the production of engineering prototypes. However, the related discipline of developing an accurate product structure breakdown can be a very good tool for prototype development. Developing an accurate product structure as early as possible in the design process and making frequent updates as the design changes provides a sound basis for accurate materials planning once the prototype stage is complete.

**Manufacturing Resources Planning (MRPII)**

MRPII systems took manufacturing planning to a higher level by expanding the scope of planning from simple material requirements to include other functional areas. This inclusion of other functions in the planning process is one of the most important contributions made by MRPII systems. Among the tools required by an MRPII system were accurate forecasting, master material data, bills of material, and a centralized purchasing system for capturing material requirements and placing orders on time and without duplication.

Accurate forecasting meant that the computerized portion of the system would be able to calculate when components and raw materials would have to be ordered if they were to arrive in time to meet schedule demands. This was also a part of the earlier MRP systems. MRPII, however, was able to make further use of forecasting information to ensure that people and equipment would also be available when they were needed.

Master material data accuracy was another vital key to successful implementation of MRPII. Master data consisted of material descriptions, supplier contact information, cost, procurement lead-time, hazardous material information (if applicable), and any other pertinent information to ensure the correct materials were ordered and processed. Different pieces of information were often provided by different functional groups; thus, close and accurate communication was a must.

Bill of material accuracy was just as important as master material data accuracy to the MRPII system. It provided the product structure for finished products and the interrelationships between individual component parts in order to produce the final product. At a minimum, bills of material provided inputs of which component parts or raw materials were required, a unique description of each material, how many of each were needed, and the supplier of each material.

Finally, MRPII provided a centralized purchasing system to collect all material requirements for ordering. Often different assemblies would utilize common component parts. Combining all requirements for a single part into one order allowed companies to benefit from economical order quantities and required fewer purchasing agents to handle the volume of purchase orders.

As with MRP systems, MRPII systems are not generally used for managing the production of engineering prototypes. MRPII methodology builds upon the foundation of MRP by continuing to stress the importance of organization and development of highly detailed product structure documentation. But it goes beyond planning for the procurement of assembly materials to include planning for all other manufacturing resources as well. Highly disciplined resource planning is the part of MRPII implementation that can best be applied to engineering prototypes.

The benefits of accurate product structure information collected into BOMs for prototype production are described in the previous section. MRPII systems require the same structure to be applied to master data for each component used in product assemblies. To be effective master data should include, at a minimum: the manufacturer's name and part number and enough unique descriptive information to distinguish different materials from each other. Additional information may include standard cost information, standard lead-time information, standard order quantities, minimum safety stock, inventory storage locations, and alternate materials that may be used interchangeably. Material master data accuracy is extremely important because it defines which materials will be procured and used to fabricate products. Prototype assembly requires the same accuracy to ensure that correct materials are used. It is not uncommon during the design phase for engineers to provide only sketchy details of the material requirements for prototypes. In such cases the best interests of the design team are served by insisting that full details be provided before master data is populated and used to procure component parts. Without careful material selection even the best designs are prone to failure.

Beyond material master and BOM data accuracy, MRPII systems are used to generate aggregate purchasing plans. By combining the material requirements of all projects, the number of purchase orders can be reduced and economies of scale enjoyed by ordering economical quantities of materials. Although the economies of scale are less applicable when dealing with small prototype quantities than when dealing with full production quantities, any effort to reduce costs by placing fewer purchase orders can equate to significant savings. Traditional prototype labs often have several designers ordering their own materials as a need arises, buying minimum order quantities imposed by suppliers. Often other designers in other parts of the company may be ordering the same materials with the same imposed minimum quantities. Utilization of MRPII procurement practices encourages a common engineering materials procurement group. This group owns the task of collecting aggregate material requirements for all prototype projects, ordering the necessary materials to meet requirements, and maintaining a stockroom to support future requirements. Pooling requirements and reducing the number of purchase orders reduces overall prototyping costs. Maintaining a stockroom provides a method of safeguarding excess materials for future use, thus reducing duplicate purchase orders, waste, and loss.

**Total Quality Control (TQC)**

While many initiatives have been developed to improve companies' productive output or product quality, TQC sought to go further and improve quality in other areas such as product design and development and materials management. In the process its proponents brought two new items to corporate toolboxes: individual accountability and continuous improvement.

In the past, quality improvement consisted of cadres of inspectors tasked with locating product defects and routing defective units to rework stations before the product could move to the next operation. TQC, in contrast, stressed the prevention of defects all along the assembly process. Individual workers (not the quality control department) became responsible for the quality of their own work. The most obvious benefit was the improvement in product quality. A secondary, and perhaps more profitable, benefit was the difference in the quality of employee's work lives. People accustomed to spending each day performing the same, and often monotonous, tasks were given responsibility for the quality of their workstation's output. And along with that responsibility came the satisfaction of knowing they had done a good job.

Workers' changing attitudes toward their jobs fostered a smooth transition to a second TQC goal: continual quality improvement. Managers who had once set quality goals for optimum performance and driven their work forces to achieve them started down a new path where there was no optimum level of performance. No matter how much better the quality became there would always be room for improvement. The changes represented a paradigm shift that could only be accomplished by workers who truly believed they could contribute to continuous improvement.

TQC's main goal is to foster an attitude of continual improvement, not only in manufacturing processes, but further, into every aspect of a product's lifecycle. TQC principles can be adapted to various parts of engineering prototype production as described in the following paragraphs.

Designers must verify assembly drawings, schematics, material specifications, etc. before presenting them to assemblers if finished prototypes meeting design requirements are to be expected. In practice, last-minute design changes are often inadvertently left off of assembly documentation resulting in time-consuming and costly rework to cut in the changes. By investing additional time prior to releasing product documentation to assemblers, the quality of design output can be greatly increased.

Prototype assemblers can apply TQC principles by continually looking for improvement opportunities in the way they perform their jobs. As the recipients of design documentation, they must be constantly looking for errors that can slow down the process. As the subject matter experts of product assembly, they can often identify better ways to accomplish tasks than can a designer whose main goal is to develop a finished product. For example a busy designer may specify a particular method for fabricating a subassembly while an assembler may recognize a simpler solution or perhaps one that cuts costs. In such cases, quality improvement dictates that the new process be adopted as quickly as possible.

TQC is also applicable to the materials function. To ensure acceptable product performance, the materials organization must work with designers to select reputable material suppliers. A core set of pre-approved suppliers is an important element for quick-turn prototyping efforts. A master list (or catalog) of engineering materials from which designers may select the majority of their components helps speed the design process. Maintaining minimum stock levels of these materials allows prototypes to be produced quicker and with less variability than when designers are forced to order materials from whichever supplier can meet a deadline. Engineering material organizations can further aid design engineering by developing sound working relationships with material suppliers. A benefit to be gained by these relationships is the ability to glean from their expertise with their materials. Most designers are quite familiar with their own product lines, but are often not as familiar with the raw materials needed to produce their products. The ability to rely on familiar suppliers to recommend the correct material solution for a given design characteristic is an invaluable aid to producing better quality prototypes and finished goods.

**Theory of Constraints (TOC)**

Introduced by Eliyahu Goldratt in the mid-1980s, TOC introduced the concept that problems with a factory's output could be traced to identifiable constraints within its processes. Tracey Burton-Houle (2001) of the Goldratt Institute presents the concept of constraints as follows:

> . . . just as the strength of a chain is dictated by its weakest link, the performance of any value-chain is dictated by its constraint. Recognizing this, the resulting steps to maximizing the performance of a value-chain are:
>
> 1. Identify the constraint.
> 2. Decide how to exploit the constraint.
> 3. Subordinate and synchronize everything else to the above decision.
>
> To improve the performance of that same value-chain, continue:
>
> 4. Elevate the performance of the constraint.
> 5. If in any of the above steps the constraint has shifted, go back to Step 1. (p. 9).

Goldratt and Cox (1986) refer to these constraining items as bottlenecks defined as "any resource whose capacity is equal to or less than the demand placed upon it." (p. 138). One of the most important processes presented by TOC was that of identifying bottleneck resources within a factory's operations (or within any process) and setting about to alleviate the system's dependence upon those resources. TOC principles pointed out that because the overall speed of a production system was determined by the speed of the bottleneck, it was vitally important that bottleneck resources only be used to process good materials. It became imperative that defective parts or subassemblies be weeded out prior to reaching the constraining points in the system. Per Goldratt and Cox (1986): "If you scrap a part before it reaches the bottleneck, all you have lost is a scrapped part. But if you scrap the part after it's passed the bottleneck, you have lost time that cannot be recovered." (p. 156). Identifying a bottleneck seems as though it would be a simple thing to accomplish. However, companies often found it difficult because of their mode of operation. Since traditional management strategy so often looked at a factory as a single entity, the solution to missed schedules was often a knee-jerk reaction to work more hours. If the reason for the missed schedules was a bottleneck operation, operating the entire system for longer periods only added more work-in-process (WIP) into the system and did little or nothing to alleviate the problem. Often the result would be large stockpiles of WIP that had the affect of cloaking the real problems. TOC principles advocated reducing the amount of WIP in the system to only the amount required for immediate needs. Reduced WIP inventories made it easier to identify bottlenecks in the system. Because of their output limitations, they quickly surfaced as the operations that were "starving" their successor operations. As a bottleneck was identified and relieved, the next worse problem area would surface as the bottleneck, and so the process continued as each system constraint was identified and corrected.

Just as in full production operations, time is of the essence during the production of engineering prototypes. Often designers are working against the clock to develop a product and introduce it to the marketplace before a competitor's product becomes available. Even delays of a few days can mean market introduction delays and lost market share. It is, therefore, imperative that prototype assembly operations be optimized by identifying bottlenecks, deciding how to deal with them, and eliminating the constraining condition(s). Whereas factory bottlenecks may include things like a metal finishing process that cannot keep pace with the demands of its successor operation or a product test center that cannot keep pace with the number of units to be shipped each day; prototype bottlenecks may show up in engineering, assembly, test, or material operations.

If, for example, an engineering documentation clerk has the responsibility for checking each BOM for component part number errors before it is passed to the assembly group, he could well become a bottleneck for the process. One possible solution would be a database of all possible component parts from which designers could select the desired component. By copying material data into the BOM format rather than manually entering it, data errors could be virtually eliminated thus freeing up part of the clerk's time to perform other duties.

Another example would be an assembly operation with an average daily output of 20 units and an inspection failure rate of 30 percent (or six units per day). If the required output to meet a deadline is 15 units per day the operation will fail to meet its requirements. The assembly operation will become a constraint for the entire production system and warrant investigation to determine root cause and corrective action. If a faulty purchased component is found to be the root cause of the failures, then replacing the component with an acceptable replacement will bring the output above the 15 unit-per-day minimum. The assembly operation will cease to be the bottleneck and focus can be brought to bear on the next largest constraining item in the process.

Each example requires examining the constraining elements of the system and determining the appropriate action to remove the constraint. Once accomplished, overall system performance is improved and resources once needed to support the overburdened bottleneck can be reallocated to more productive efforts.

**Lean Manufacturing (LM)**

As its name implies, Lean Manufacturing espoused the idea of using minimal resources to accomplish the same amount of work as traditional manufacturing practices. In addition to smaller, more versatile workforces and less capital equipment, LM also involved reducing the amount of on-hand inventory and work in process (WIP) and the costs associated with these.

Two very important (and somewhat related) practices invoked by companies implementing LM were moving workstations closer together and moving inventories away from central storerooms and instead to their actual point of use.

By changing the work structure to one with fewer individuals performing multiple roles, manufacturing engineers were able to develop multi-purpose workstations. This not only allowed assembly lines to be condensed to free up valuable factory floor space for new business opportunities, it also allowed faster conversions from one product to another. Still another advantage was that of allowing workstations to be placed closer to one another, thus, reducing the amount of material handling required to move WIP from one workstation to another. By adopting an LM strategy companies were often able to shift the work of full-time material-handlers (certainly a non-value-added function) to more productive activities.

A related innovation encouraged by an LM strategy involved moving raw material and component inventories out of central storerooms and to their point of use on the factory floor. Workstations were designed to have the materials needed for their operations close at hand. This again helped reduce the need for dedicated material handlers. Instead of using traditional kitting operations to collect the materials required for each production lot and then transferring them to the assembly area, the materials were simply stored in the assembly area. Workers took what was needed for their current operations as the need arose. Replenishment of floor-stock could be accomplished in a number of different ways including: stockroom personnel restocking from a central inventory location, third party inventory management personnel restocking from an on-site inventory location, and "milkman" vendor replenishment wherein a vendor representative visited the facility on a regular basis and restocked to predetermined inventory levels. A major advantage to having third-party and milkman types of inventories was that cost of raw material inventory was only incurred when the materials were actually consumed for production purposes, thus, eliminating raw material inventory carrying charges.

LM concepts essentially represent a conservation program for manufacturing operations. As the name (lean manufacturing) implies, manufacturing engineers attempt to trim away excess workspace, tools, equipment, materials, and labor. This conservative approach to manufacturing resources has brought about many improvements to American factories. LM itself, however, has not brought about the same level of improvement to engineering prototype assembly processes because these principles have by-and-large always been used in the prototype world. Only those companies currently using their normal factory production lines for making engineering prototypes will find improvement opportunities by utilizing LM for the prototype effort.

A quick review of the prototype assembly process should suffice to illustrate. As has been discussed earlier, engineering prototypes serve to provide engineers with a tangible example of new product designs or innovations to existing products. Generally, only a limited number of prototype units are produced (just enough to allow engineering to test the finished product against design specifications). Because of the variety of products that can be in development at any given time, prototype assembly workstations tend to be general purpose, laboratory-type spaces. Machining operations are performed using general-purpose machines (basic drill press, milling machines, lathes, etc.). Specialized equipment intended to reduce manual labor is added only after a product goes into full production. In most cases, only a handful of workers are involved with fabricating prototype units (often design engineers provide some or all of the labor). Long-standing engineering practice involves keeping a limited amount of raw material stock in prototype assembly areas to support prototype assembly. This serves to reduce time lost to having the materials delivered either from central storage locations or outside suppliers. Because of the smaller work areas, tools and equipment limited to the basics, a small number of people, and on-hand materials, prototype operations have enjoyed many of the benefits of LM for generations.

**Six Sigma**

Brought to the forefront of the quality movement by early successes at Motorola, Six Sigma programs have gained popularity among American companies. Companies focusing on Six Sigma improvements desired to go beyond making simple incremental improvements to their operations. Their desire was to identify single, strategic operations where improvements would bring about immediate positive results, then move on to the next strategic step, etc. Often referred to as "picking the low-hanging fruit", this approach allowed organizations to realize enormous strides toward process improvement in a relatively short period of time. In fact, many proponents of Six Sigma strategies focus on selecting projects that can be completed in four months or less.

Full-scale production operations lend themselves better to the Six Sigma approach due to the complexity of their processes. The more steps a process has, the easier it is for inefficiencies to be cloaked by the sheer magnitude of "busy-ness". However, the basic Six Sigma approach can be applied to engineering prototypes to weed out unnecessary steps that may hinder the goal of a quick product introduction. Documentation is an area often blamed for delayed product introduction and would provide fertile ground for process improvement using Six Sigma techniques. Many design organizations continue to rely on paper copies of design documentation (assembly drawings, schematics, bills of material, material specifications, etc.). Approval of such documents requires the hard copies to be routed from one person the next in a serial fashion. The second person on the approval list cannot proceed until the first person reviews the document and passes it on. The third person does not receive the document until both the first and second have finished, etc. Successful implementation of document approval using this scenario is based on the model of everyone on the approval list reviewing the document as soon as it is presented, approving the change(s), and passing it to the next person without delay who will in turn be waiting for its arrival, etc. By identifying this as a major slowdown, organizations can investigate means of improving the process. One possible solution being to route electronic copies of documents to each approve simultaneously and have each respond with approval or needed changes to the originator. This eliminates the wait time associated with the paper trail scenario. Other areas of the prototype production cycle could be addressed using the same principle of identifying and focusing on improvements to those few steps in the process that can best increase the value of the process.

**ISO 9000**

Although not technically a manufacturing philosophy, the ISO 9000 series of quality specifications have benefited numerous companies in their quest for improved product quality. Introduced by the International Organization for Standardization (ISO) these standards were developed "to provide worldwide standards that will improve operating efficiency, improve productivity, and reduce costs." (Stevenson, 1999, p. 432). AT&T's Corporate Quality Office (1995) captured perhaps the two most important ideas brought to industry by the ISO 9000 standards when it says: "There are three basic principles of the contractual ISO 9000 standards that lead to improved business processes:

- Processes affecting quality must be documented.
- Records of important decisions and valuable data must be retained.
- Compliance to ISO 9000 results in continuing improvements." (p. 4).

The first tool of interest is that of documenting business processes. Following the ISO 9000 guidelines will generally lead to *improved* product and process quality. However, from their inception, the primary purpose of the guidelines has been to assist companies in achieving *consistent* quality. By documenting manufacturing processes companies were able to reproduce their operations time and time again with fewer deviations. Assembly operations in traditional manufacturing organizations were often carried out by the same individuals for many years with new operator training consisting of word-of-mouth instructions. Often important details were relegated, at worst, to the memories of key employees and, at best, to sketchy notes tucked away "in a drawer somewhere." Implementation of the ISO 9000 standards forced companies to document their procedures and then to follow the documented steps to remove as much variability as possible from each operation so that products of consistent quality could be produced from one manufacturing lot to another. A common slogan used to describe the ISO standards was simply: "Say what you do and then do what you say."

A second tool of interest driven by the ISO 9000 standards was that of identifying pertinent data points (often referred to as metrics) and then recording measurements of these metrics at regular intervals. Examples of useful metrics include:

- the amount of time required to complete an entire assembly
- the amount of time required to complete an engineering change order
- the number of subassemblies rejected due to paint scratches
- the number of integrated circuit packages with bend leads preventing accurate placement, etc.

By collecting data about these and many other metrics and analyzing the data to identify the root cause of problems, process changes could be made to prevent problem recurrence. It is important to note that whereas simply documenting a process only allowed companies to achieve consistent product quality (whether good or bad), identifying and measuring the right processes and analyzing the data allowed the same companies to progressively increase and sustain their levels of quality.

It should be noted that adherence to the ISO standards does not in itself guarantee any level of output quality. The standards have been developed to ensure only that a consistent level of quality can be achieved if the standards are adhered to. An operation incapable of producing good quality output will not automatically be improved by adopting ISO standards, although its deficiencies will likely be identified as targets of improvement.

ISO implementation can be a very important asset to the engineering prototype phase of a product's lifecycle. Often aggressive scheduling of a new product's introduction to the marketplace drives a frenzied approach to producing early prototypes. In this scenario assembly drawings may be haphazardly changed without following normal engineering change order policies. Sometimes changes may be implemented on the lab bench without capturing them in assembly documentation. Component value changes may be made on the test bench to tune an electronic circuit without the changes being added to the bill of materials. Engineers and managers have long rationalized these types of changes as necessary to meet aggressive product development schedules with the understanding that the errors would be caught "down the road" before the product entered full production. The sad truth, however, is that these types of errors are often not caught soon enough to prevent costly errors. Two examples should suffice to illustrate the dangers involved. First, component changes that are not captured in assembly documentation lead to incorrect parts being procured driving up material costs and delaying production while the correct materials are procured. Second, deleted assembly requirements that are not properly documented lead to engineering setup charges for operations that are no longer required. Careful documentation of standard prototyping processes followed by strict adherence to the procedures helps eliminate these kinds of errors. Then by identifying metrics that indicate how well the processes are being followed, prototyping efforts can be measured and their performance judged against stated goals. For example, by measuring how often materials are stranded in inventory due to undocumented design changes, a prototype material planner can get a feel for how closely the prototype process is being followed. Establishing metrics and tracking performance against them can be an important tool for quality improvement, however, caution should be exercised when selecting metrics. Data measurements tend to drive behavior patterns. If the wrong data points are measured and reported, unacceptable behavior can result. Therefore, when identifying appropriate metrics to be tracked and managed as part of an improvement strategy, managers must be careful to keep an eye on the "big picture" lest improving one process lead to less than optimum system performance.

## Total Quality Management (TQM)

As one of the later management philosophies, TQM was able to build upon the foundation of earlier programs. It focused a great deal of attention on continual improvements to every conceivable part of a company's operations. Managers were encouraged to make business decisions based on "facts and data" rather than what "seemed" right at the time. Statistical quality control (SQC) became a significant contributor to the success of organizations embracing TQM. By taking statistically significant samples from process outputs and comparing them with a predetermined standard, a process could be judged whether in tolerance or out. If the results of the sampling were unacceptable, the process would be stopped until corrective action was taken. Table 2 lists some of the benefits to be enjoyed from a properly executed SQC (also referred to as Statistical Process Control or SPC) program.

| | |
|---|---|
| 1. | Results in a more uniform quality of product |
| 2. | Provides a means of catching errors at inception |
| 3. | Reduces inspection costs |
| 4. | Reduces the number of rejects and saves the cost of material |
| 5. | Promotes an understanding and appreciation of quality control |
| 6. | Improves the relationship with the customer |
| 7. | Points out trouble spots |
| 8. | Provides a basis for attainable specifications |
| 9. | Provides a means for determining the capability of the manufacturing process |

**Table 2:** **Benefits of Implementing an SPC Program** (Amrine, Ritchey, Moodie, & Kmec, 1993, p. 425)

TQM implementation required a strict adherence to identifying key metrics, taking data, and extracting from that data the information needed to drive quality improvements. Stevenson (1999) describes the TQM approach in five steps:

1. Find out what customers want.
2. Design a product or service that will meet (or exceed) what customers want.
3. Design a production process that facilitates doing the job right the first time.
4. Keep track of results.
5. Extend these concepts to suppliers and distribution. (p. 492).

Three tools utilized by TQM advocates are worthy of mention for the current study: competitive benchmarking, employee empowerment, and a team-based approach to operations.

Jack Welch, former CEO of General Electric, has been credited as attributing the ultimate competitive advantage for a company with its ability to learn lessons from any source, anywhere and to rapidly apply the newfound knowledge to its processes. Competitive benchmarking captured this idea by introducing the idea of looking for improvement ideas in the way other companies did business. This most often involved a company comparing its current business practices with those of other companies thought to be the best in their class. The common steps of competitive benchmarking are:

1. Find out what organization does it best?
2. Find out how they do it.
3. Determine how we do it now.
4. Determine how we can change to match or exceed the best.

For benchmarking to be successful, each participating company would agree to share information with the other(s) – with exceptions made for information of a proprietary nature. Successful benchmarking often required an “out-of-the-box” mentality. Companies had to recognize that the organization representing the best in class for a particular operation might well be in a completely different industry. Hammer and Champy (1993) suggest that “if a team is going to benchmark, it should benchmark from the best in the world, not the best in its industry. If a team’s company is in the consumer packaged goods business, the question is not who is the best product developer in packaged goods, but who is the best product developer – period.” (p. 132). For example, an electronics manufacturer desiring to benchmark the best storeroom inventory practices might find itself studying a company in the automotive parts industry. At first glance this might seem odd, but because auto parts dealers have their inventories linked to the make and model of individual automobiles by a detailed product structure (essentially a bill of materials), their inventory practices can be very helpful to electronics manufacturers. Hence, Welch's comments that successful companies must be able to learn lessons from any source and put what they have learned into practice became extremely important for benchmarking partners. Companies had to determine which of their processes were most important to their customers and by viewing those processes through their customers' eyes figure out who performed them better than anyone else. The answer became the targeted benchmark partner. Once the partner was identified and agreed to the partnership, its processes could be systematically studied to identify which pieces could be successfully implemented by the company sponsoring the study. Numerous companies have participated in benchmark studies and found ways to improve their operations.

Unfortunately, fewer companies have examined a second (perhaps less glamorous) type of benchmarking – internal benchmarking. Internal benchmarking involves the same processes as external benchmarking, but calls for examining the internal operations of a company instead of looking outside the company. Emphasis is placed on designing processes that utilize lessons learned from previous process development. The late Jerry Jenkins, former Chairman, President, and CEO of Texas Instruments, once lamented: "'If we only knew what we know at TI.' Jenkins was expressing what many managers are rapidly beginning to realize: that inside their own organization lies, unknown and untapped, a vast treasure house of knowledge, know-how, and best practices." (O'Dell & Grayson, 2002, p. 1). A 1994 benchmarking study made by the American Productivity and Quality Center (APQC) found that a practice could remain unnoticed in a business for years and even when recognized could take more than two years on average before other locations began trying to apply it. (O'dell & Grayson, 2002, p. 2). A sound internal benchmarking philosophy encourages organizations to capture "what they know" by documenting project successes for future emulation and project failures for future avoidance. Concentrations of study are limited by the number of different in-house operations, but any internal benchmarking has several advantages over external benchmarking including: reduced cost, faster response time, and the beneficial results of having employees know that their past experiences are being drawn upon for their company's future success.

Although not limited to the TQM movement, employee empowerment initiatives were used extensively by companies espousing TQM strategies. As its name implies, employee empowerment allows workers a certain level of autonomy with regard to their assignments. For example, assembly line operators were given the authority to stop the line if they detected a defective condition that could not be corrected immediately. Furthermore, they had the authority to keep the line shut down until the problem was corrected to their satisfaction. In other cases, employees were allowed to participate in the design of products and manufacturing processes. Traditional factory operations assumed that design engineers were the subject matter experts for every aspect of product design. TQM, on the other hand, recognized that the people who spent every day assembling products could play an important role in designing new products. They could, for example, share their experiences with brittle plastic housings and suggest ways of reinforcing known stress points, describe time gains to be realized if snap-fit assemblies were designed instead of screws and nuts, etc. Including workers in the design process provided an even further advantage, however, in the motivation of the workforce. Suddenly workers who had seen new product or process designs duplicating the same errors for years had a chance to eliminate the problems from future designs. Factory floors took on an air of experimental laboratories where suggestions could be implemented, tested, and changed (several times if necessary) until an optimum solution was found.

TQM methodologies didn't stop with simply empowering individuals in the workforce. It went further to encourage the use of self-motivated work teams. Traditional work units consisted of a group of employees (often performing similar operations such as a group of welders, electronic testers, inspectors, etc.) and a supervisor who directed their efforts. Self-motivated work teams, in contrast, consisted of teams of employees empowered to decide what they worked on, in what sequence, and in accordance with what schedule. Although team members still reported to supervisors, they were allowed the autonomy to make critical decisions regarding their work activities. Many teams were even allowed to discipline team members' unacceptable performance and to make hiring and firing decisions. Teams were expected to perform such tasks as identifying appropriate performance metrics, collecting data for each metric, evaluating the data to identify process problems, and taking the appropriate corrective action to prevent recurrence of problems. Furthermore, these teams were given the authority to call in subject matter experts from areas outside their membership to assist with their quality improvement efforts. As with individual employee empowerment efforts, successful work team implementation brought about more than process or quality improvements. They also greatly improved employee morale by showing workers that their experience was valued, that their ideas were important, and that they were trusted to do the right things in the right sequence and at the right time for the benefit of the company. Some companies even modified their pay structures to allow high performance teams to share in the value they added to their companies by enjoying pay raises linked to their successes.

Benchmarking can be a very valuable tool for developing a better engineering prototype process. Engineers involved in the development of new products find themselves at the mercy of customer demands. Often these demands require features or materials with which the design team has no experience. In such cases, benchmarking allows the designers to borrow best practices from others who have already been down that path thus saving the time and costs associated with starting from scratch. It should be noted, however, that a full-fledged benchmarking plan can take months or even years to complete. To be useful for prototyping, a scaled-down benchmark plan should be developed to allow more flexibility in the study and to allow for quicker results. Although accelerated benchmark studies may result in less optimum changes; quicker results are a necessity in order to get new products to market as soon as possible. Product development engineering and prototype assembly management should be constantly scanning internal company operations to identify process improvements that can be adapted to prototypes to improve product design cycle time.

A second tool utilized by TQM advocates that is applicable to developing engineering prototypes is employee empowerment. By granting a certain degree of autonomy to workers and encouraging their input for the design of new products and processes, design engineers can gain a wealth of knowledge that might otherwise be missing from the product development cycle. It is important for workers on an assembly line to be able to stop production if they see a defect before thousands (or more) items are produced with the defect. In the same way it is important for employees involved in developing engineering prototypes to point out ways to make products better as early in the design cycle as possible to avoid unnecessary costs and time consumption. Everyone involved in prototype design, development, production, and test should be encouraged to look for things that are wrong, out of place, incorrect, sub-optimized, too costly, too wasteful, etc. In short, each employee should share (and feel) an equal level of responsibility for developing new products and getting them ready for market as inexpensively as possible, in the shortest time possible, and with the best quality possible. To be successful each person involved with producing engineering prototypes must consider himself a member of a team whose goal is to win, and this leads to the third TQM tool applicable to developing engineering prototypes: self-motivated work teams.

Developing self-motivated work teams is an important step toward enjoying the full benefits of TQM. The goal is to develop a team of individuals who understand that success comes easier when everyone works toward a common goal without having to wait for supervisory direction to carry out each task. This frees up managers for longer range planning activities. Heifetz and Laurie (2002) assert that

> "business leaders have to be able to view patterns as if they were on a balcony. It does them no good to be swept up in the field of action. Leaders have to see a context for change or create one. They should give employees a strong sense of the history of the enterprise and what's good about its past, as well as an idea of the market forces at work today and the responsibility people must take in shaping the future." (p. 15).

In the fast-paced world of prototyping, people are often required to perform tasks outside their normal areas of expertise to expedite task completion. Team members whose leaders have followed the advice of Heifetz and Laurie are better equipped to understand these requirements and pull together while people in traditional work environments tend to resist moving out of their normal routines. Development of work teams allows team members to examine their workload, decide the importance of each item, and work together to complete each task in the order of its importance. It also allows them to decide, if necessary, to suspend work on a current task to work on a more pressing matter without having to wait for permission from a supervisor. This kind of empowerment allows organizations to enjoy improvements in speed and agility that bring a product prototype to completion much faster than could be accomplished using traditional manufacturing concepts. And at the same time improved team member morale is an invaluable by-product.

## Concurrent Engineering

Although not necessarily a quality initiative in itself, concurrent engineering is a philosophy that has greatly enhanced the ability of companies to outperform their competition and improve the quality of their products. At a minimum, concurrent engineering brings design and manufacturing engineers together during the early design stages of product development to collaborate on the best processes for producing the product. A more expanded view includes assemblers, test engineering, repair technicians, suppliers, marketing representatives, purchasing, and even customers in the early stages of product/process development. Traditional product design involved having each department do its part before handing off the design to the next department. Design flaws found in later stages required routing the design back up the chain for redesign slowing down the product introduction process and often leading to cost overruns. Concurrent engineering brought everyone involved in the design process together from start to finish. Open communications between different functions was key to design success. Often people from different disciplines were relocated to work side by side to encourage them to get to know their counterparts and how their individual parts of a design related to one another. Adopting this practice allows representatives from each functional area to look for potential problems in a proposed design before material and labor costs are incurred while at the same time fostering a sense of trust between different functional areas. Beyond the areas of product design, manufacturing engineers were brought in early in a product's life cycle to point out potential areas of conflict with manufacturability that if left unchecked could add to production costs. Test engineers were included in the early design stages to assist with developing product characteristics to aid in final test and evaluation. Repair technicians were invited to share hints on making products that could be disassembled easier to make necessary repairs or upgrades. Materials procurement personnel were included in early design discussions to help identify long lead-time or high cost materials that might be easily designed out and replaced early in the design cycle. Often even suppliers were brought into early design meetings to assist with the selection of materials or components that would meet the product requirements at the least cost. By combining representatives of each functional area in the design process – together – companies were able to shorten product development time, reduce costs, and get products to market faster than ever before.

Numerous examples can be presented to illustrate concurrent engineering's importance. Allowing a test engineer to review the plans for a new circuit board may reveal that the designers have forgotten to include a connector to allow a microprocessor circuit to be tested before final assembly. Bringing assembly workers into a discussion of a proposed engine design for a new sedan may bring to light the fact that, without design changes, there will be no way to replace one of the spark plugs after the engine is installed. Purchasing representatives brought into early discussions may identify materials that are either too expensive or not available in time to meet schedule requirements. Success comes much easier to companies where information between functional groups is both sought and shared.

Producing engineering prototypes involves most of the same steps used in full-scale production; therefore, the benefits of concurrent engineering principles can be enjoyed even in the early stages of product development. Because prototype teams tend to be much smaller than full production staff, communications can be carried out faster and decisions made in a more timely fashion. Smaller teams typically mean less bureaucracy is involved with making changes. Often documentation rules are less stringent allowing for quicker changes to be made (although this can be a danger if changes are allowed to take place without adequate documentation) and often prototype labs are located in close proximity to designers' workstations to further expedite communications. However, in some prototyping environments not every function that will be involved in full production is represented in the prototype lab environment. To ensure success, the prototype team must strive to identify all stakeholders in a new product design and to include them as early in the design process as possible to eliminate costly errors.

**Human Resource (HR) Management**

Another area (again not specifically a quality improvement initiative) that has played an important role in American industrial improvement in recent years is that of human resource management. Traditional factory management practices tended to treat workers as less important than engineers or managers. They were viewed in much the same way as pieces of machinery to be exploited to their fullest potential and then often discarded. In essence workers were considered as expense items, necessary for a business to succeed but at the same time representing a cost the company had to bear. Modern human resource management introduced a different way of viewing workers – as assets, not expenses. As the name implies, individuals were still regarded as resources, but more as capital investments instead of expense items. Per former U. S. Secretary of Labor, Robert Reich, "The core of the new enterprise in the 21st century will be talented people capable of quickly assimilating new knowledge and learning from one another. That means management must change its attitude that workers are costs to be cut. The high-value organization can only succeed if it is people-centered and views workers as assets to be developed." (Verespej, 1999, p. 2). Rather than train factory employees to perform monotonous and often mundane tasks, expecting them to perform them day after day, and then replacing them when they could no longer keep up; modern human resource management recognized human potential to adapt to changing environments and rapidly acquire new skills. This new method of nurturing employees has been captured by Capt. Michael Abrashoff (2002) when he describes his organizing principle as: "the key to being a successful skipper is to see the ship through eyes of the crew. Only then can you find out what's really wrong and, in so doing, help the sailors empower themselves to fix it." (p. 13). By creating an environment where employees could become a part of designing their work systems and fostering continual learning initiatives companies were able to develop highly skilled workforces able to quickly respond to market trends and fickle customer requirements.

In addition to providing training opportunities for employees, company managers began to tap into the creative abilities of employees. Risk taking was encouraged in many companies to give employees the ability to utilize their varied talents to work out innovative solutions to problems and design new products outside normal engineering channels. Where traditional management practice involved punishing efforts that failed, new strategies stressed the need to use failures as stepping stones to success. By careful examination of failed projects, companies were better equipped to avoid pitfalls on future projects as discussed in the section on internal benchmarking.

Finally, modern human resource management realized that to encourage talented individuals to continue to improve both themselves and their organizations, their contributions would have to be both recognized and rewarded. HR departments expended enormous amounts of effort to develop employee recognition programs to bring both employee and team successes to the forefront. Such recognition not only helped further a sense of pride in workers' performance, but also encouraged people who otherwise might sit on the sideline to get involved with improving their organizations. Richard Teerlink, former CEO of Harley-Davidson relating part of Harley's success says "we knew we had to create an organization where *all* people feel important because the only sustainable competitive advantage is people. You have to invest capital and systems to support the investment in people." (Verespej, 1999, p.1). Rewarding people for success took many forms including: lunches to honor progress, paid time off from work, incentive bonuses, and even pay raises. Some companies even went beyond rewarding employees for their successes and even rewarded failures. Based on the old saying: "A person who never fails, never tried to accomplish anything", many HR departments decided that the effort of attempting to make a contribution to organization excellence was enough to justify a reward. If an attempt was successful, then the reward was even more justified.

Obviously HR practices put into place in recent years apply equally to all employees whether they are involved in production or prototyping efforts. But, for the current study, it is important to examine those HR initiatives that are most likely to improve the early prototype stage of new product development. In much the same way that concurrent engineering brings about improvements by including everyone in the design process; recent HR initiatives bring about improvement by giving everyone on the team the recognition they deserve. By fostering a work environment where each team member feels respected and valued, modern HR practices provide the nudge that some employees need to speak up and add their ideas to an organization's body of knowledge. Verespej (1999) quoting former U.S. Labor Secretary Robert Reich asserts "competitiveness is what you can do uniquely. And the only thing that is unique within each company is the capability of its people. So if a company's workers add more value, [the company] will do better." (p. 2). Where in the past assembly workers might have felt their opinions and experiences weren't valued as much as those of design engineers; the modern prototyping team recognizes that everyone's input is important. Cost and time constraints require that a product be developed as quickly and cost-effectively as possible and any idea that will help get a new product to market before its competitors is an idea that needs to be heard. For example, a recommendation to outsource a subassembly to a supplier who offers quick-turn services for small quantity prototypes could shave days off the design cycle. The subassembly production effort can be brought back in-house later when the time to develop the capabilities in-house can be spared. As another example, consider a suggestion to eliminate the installation of a heat shroud on prototypes that will not be subjected to conditions above room temperature during evaluation. This would save the cost of the shroud, assembly labor, and unnecessary assembly time. Design engineers may, in the rush to complete a design documentation package, miss little details that other members of the prototype team will recognize immediately. Abrashoff (2002) interviewed every member of his crew to get their opinion of the condition of ship operations and relates: "From those conversations, I compiled two lists of all the jobs performed on the ship. List A consisted of all our mission-critical tasks. On List B were all our non-value-added chores – the dreary, repetitive stuff, such as chipping and painting." (p. 47). One sailor presented a solution to alleviate the repetitive task of painting (performed up to six times a year). He suggested replacing the iron bolts that caused rust stains to run down the sides of the ship with stainless steel ones. It was a simple solution to be sure, but one that had been overlooked for many years because no one had bothered to ask the individuals who were constantly performing the non-value-added task.

Modern HR initiatives encourage people to take risks. By encouraging each team member to make suggestions without fear of reprisal or ridicule, prototype teams can reap the benefits of everyone's experience. But recent HR initiatives have gone beyond encouraging participation to include rewarding team members for their efforts. In the prototype production environment improvement suggestions need to be recognized and rewarded. Even suggestions that do not produce the desired results should still be recognized as important contributions. Failures should be investigated to see what went wrong and the information gleaned used to prevent similar failures in the future. Jennings and Haughton (2002) suggest that

> every time a company decision backfires or one of its initiatives fails, the following questions should be asked and the answers recorded for future reference:
>
> - What were the unexpected failures the last time we did something like this?
> - Did we learn something we can capitalize on this time?
> - What's changed this time around?
> - Why won't the same failures happen again?
> - Did our failures keep us from achieving what we set out to achieve?
> - How much effort might I/we waste dealing with failures? (p. 53).

They further suggest that

> fast thinkers learn from their past successes as well as their failures and ask:
>
> - What were our unexpected successes the last time we did something similar?
> - Did we learn something we can capitalize on this time?
> - Did we leverage what we learned the last time around?
> - Was it just the nice surprises that got us where we wanted to be?
> - Will success this time require nice surprises? (p.54).

By asking these types of questions and keeping records of the answers, companies send a clear message that ideas are valued and the results of those ideas will be used as learning tools to make their organizations better. This principle is equally applicable in production environments, in engineering prototype environments, and across all corporate processes.

**SUMMARY**

Heavy global competition has forced American manufacturing companies to examine each of their processes and identify improvement opportunities in order to remain profitable and competitive. Customer expectations for high quality, low cost, and immediate delivery continue to drive factories to achieve levels of speed and agility never before achieved. Capturing acceptable market share means products must be introduced to the marketplace soon enough to gain widespread acceptance before competitors' products become available. But this alone cannot ensure success. Products must also be viewed by consumers as cost-effective and possessing the highest quality possible.

Modern production and operations management practices have allowed companies to achieve tremendous operational improvements in manufacturing in recent years. This course has identified the pre-production prototype phase of the product lifecycle as an area often overlooked by corporate process improvement champions. As part of the new product introduction process, prototype production represents a significant improvement opportunity for companies seeking to shorten their time to market for new products. This course was designed to review which production and operations methodologies are best suited for application to engineering prototypes and how best to adapt them to meet the rigorous requirements of the new product introduction environment.

By taking a systems analysis approach to the product lifecycle we have examined whether tools applicable to one phase of the cycle (full-scale manufacturing of released products) are equally applicable to the other phases of the cycle and in particular to the production of engineering prototypes. With as much as 70 to 80 percent of a product's lifecycle cost determined during the design phase it becomes critical for companies to identify cost reduction possibilities as early as possible.

The early development stage of the product lifecycle is where many of the most costly elements of a product are defined and locked in place. It is here that materials are selected and qualified for inclusion in the product design. It is here that product design parameters define the operations required to assemble the product. It is here that product layout and physical features are established that will determine if the product can be effectively tested and if damaged or defective product can be economically repaired. Excessive material costs that are not identified during this stage are passed on to manufacturing where they are multiplied by production volumes over the entire life of the product. Failure to identify design features that require excessive machining, handling, or fixturing at this stage translates into ongoing assembly costs that will be compounded during the life of the product. Failure to recognize product features that complicate product testing results in higher inspection costs during manufacturing. And, failure to provide product designs that can be easily repaired instead of having to be replaced can result in loss of customer satisfaction and reduce the number of repeat customer sales. Adoption of the improvement tools presented in this course results in cost, time, and quality improvements during both the prototype production stage of the product lifecycle and across the entire life of the product.

The recommendation from this study is that companies currently viewing the development and production of engineering prototypes as a "necessary evil" that must be tolerated with little room for improvement should take another look. By utilizing the same tools and the same discipline applied to other areas of the production process, similar improvement results may be achieved. By identifying and correcting process and product flaws as early as possible in the product lifecycle, companies can enjoy greater profitability over the entire life of their products. This is in contrast to traditional methods of rushing through the product development cycle and looking for problems only after the product is released to the factory for production. Beyond the point of manufacturing release, process and product improvements become far more costly because they involve a much larger field of operations. Material changes can lead to either stranded inventories or delayed changes while old revision materials are consumed. Drawing changes can lead to delays as each stakeholder becomes involved with approvals. Changes to assembly operations can lead to delays while employees undergo additional training, while assembly lines are re-tooled, while assembly layouts are redesigned, etc. The prototype stage of product development, on the other hand, involves a relatively small team of people who can react to changes with speed and agility, thus allowing improvements to be implemented in what approximates real time. The benefits of using the engineering prototype process as a spring-board for product and process improvements have been shown to support the business goal of making money now and in the future and to assist manufacturing companies in their efforts to reach world-class performance.

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# APPENDIX

## Summary of Quality Improvement Methodologies

| Methodology | Tools, Techniques, and Key Points |
|---|---|
| Quality Circles | • Employee involvement<br>• Increased productivity<br>• Increased motivation<br>• Leverage of employee talents & skills to resolve quality problems |
| Just-in-Time | Kanban<br>• Visual system of restocking wherein an empty bin triggers the need to replenish inventory<br>Market of one<br>• Drive toward producing smaller lot sizes (ideal lot size of one piece) to eliminate the possibility of building multiple defective or "old rev" parts |
| Material Requirements Planning (MRP) | Scheduling<br>• Establish material reorder points<br>• Answers questions:<br>o What is required?<br>o How much is required?<br>o When is it required?<br>• Inputs to MRP system:<br>o Master schedule<br>o Bill of Material (BOM) files<br>o Material master records<br>o Inventory records files<br>• Benefits:<br>o Low levels of work-in-process (WIP)<br>o Ability to manage material requirements<br>o Ability to evaluate capacity requirements generated by master schedule<br>o Means of allocating production time |
| Manufacturing Resources Planning (MRPII) | Scheduling<br>• Expands on MRP to include **ALL** manufacturing resources<br>• Development of Master Schedule by:<br>o Production<br>o Marketing<br>o Finance<br>Planning<br>• Demand Forecasting<br>o Procurement ensures materials on hand to support manufacturing<br>o Assembly & Test ensure shared resources available for production<br>• Capacity planning<br>o Ensures existing facilities & resources sufficient to meet demand<br>Master Data<br>• Eliminate duplicate materials<br>• Standardize material descriptions<br>• Provide hard link between material master information and bill of material files (eliminates keying information more than once)<br>• Provide component selection tools for engineering<br>• Standardize component base (one std tolerance vs. several)<br>• Establish approved supplier list (ASL)<br>Inventory Control<br>• Controlled access storeroom<br>• Cycle counting to monitor inventory accuracy<br>• Establish material reorder points<br>Purchasing<br>• Centralize purchasing activities |

| **Methodology** | **Tools, Techniques, and Key Points** |
|---|---|
| Total Quality Control | Apply quality improvements to<br>• Manufacturing<br>• Product design (new concept)<br>• Incoming raw mat'ls (new concept) |
| Theory of Constraints | • Identify system constraints (bottlenecks)<br>• Reduce system dependence on bottlenecks by off-loading everything possible to different work centers<br>• Stagger work schedules to keep bottlenecks operating through normal meal and break times<br>• Ensure that bottlenecks only process known good materials |
| Lean Manufacturing | Kaizen<br>• Remove tools, materials, paper, etc. not necessary for current operations<br>• Clean work area<br>• Locate work stations closer to each other to reduce material handling and hand-off delays<br>Material Handling<br>• Reduce material handling by moving commonly-used parts to assembly area<br>Distributed Assembly Areas<br>• Place assembly areas adjacent to critical design labs for quick-response assembly & rework<br>Facilities Layout<br>• Lay out work centers to reduce material handling & transit time<br>• Clearly identify work centers<br>Vendor Managed Inventory<br>• 3rd party agreement for APL components in prototype quantities to reduce in-house inventory<br>• 3rd party management of on-site prototype inventory |
| Six Sigma | • Focus on a few key issues that will make the most difference<br>• Strive for "quantum leaps" rather than incremental improvements<br>• Utilizes a 4-step process:<br>o Focus the improvement process<br>o Reduce delay, defects, and costs<br>o Stabilize and sustain the improvement<br>o Recognize, review, and refocus efforts |
| ISO 9000 | Document Processes<br>• Evaluate the way a job should be done and document the process<br>• Follow the documented procedures – if they need to be modified, change the guiding document<br>Record Data<br>• Identify pertinent metrics and collect data<br>• Review the data and use results to drive necessary changes<br>Periodic Audits<br>• Audit the system periodically to ensure all major processes are properly documented and followed |

| Methodology | Tools, Techniques, and Key Points |
|---|---|
| TQM | SPC tools<br>• Frequency distribution<br>• Control charts<br>  o Check Sheet<br>  o Flowchart<br>  o Scatter Diagram<br>  o Histogram<br>  o Pareto Chart<br>  o Cause & Effect Diagram<br>• Acceptance sampling<br>Shewhart cycle:<br>• Plan<br>• Do<br>• Study<br>• Act<br>Benchmarking<br>• Internal – be sure each process is designed utilizing lessons learned from other in-house processes<br>• External – examine competitors and implement best practices |
| Concurrent Engineering | • Involve procurement early in design process<br>• Involve suppliers early to identify new technologies for design inclusion<br>• Identify long-lead items early in design process<br>• Manufacturing engineering reviews preliminary designs for manufacturability<br>• Test engineering reviews preliminary designs for testability<br>• Repair engineering reviews preliminary designs for repairability<br>• Materials Engineering reviews preliminary designs to identify material sourcing or incompatibility issues |
| Human Resources | People<br>• Recognize & reward talent<br>• Provide training<br>• Encourage risk-taking<br>• Provide means for employees to provide input |