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TQM Improves Productivity and Quality of Manufacturing

John Schneider
Textron Marine Systems

Textron Marine Systems is one of fifteen divisions within the Aerospace Technology business sector of Textron, Inc. The other two business sectors are Commercial Products and Financial Services. Textron, Inc. operates over 142 manufacturing facilities across the United States and employs about 54,000 workers. Textron Marine Systems headquarters and shipyard are located in New Orleans. It has four other facilities including Panama City, Florida (test and training), Norfolk, Virginia (product support), Camp Pendleton, California (product support), and Picayune, Mississippi (rubber fabrication). In 1993, corporate revenues reached $9.1 billion. In 1992, Aerospace Technology accounted for 44% of total corporate revenues and 37% of profits.

Textron Marine specializes in the manufacture of air-cushion supported ships. One type of ship is an air cushion vehicle (ACV), which is an amphibious vehicle that is supported predominately by a cushion of air between the vehicle and the surface. Lift fans are used to supply air under pressure to the air cushion, which is contained by a flexible seal, or skirt, around the entire periphery of the hull, making it amphibious. Air propellers are used for propulsion. Another type of ship is a surface effect ship (SES), which is a waterborne, air supported craft with catamaran-style sidehulls. The SES uses a cushion of air trapped between the sidehulls and flexible bow and stern seals to lift the center portion of the hull clear of the water. Water propellers are used for propulsion. Both ACVs and SESs are used by the U.S. Navy, Coast Guard, and Army Corps of Engineers. They are used by several cities for ferry service and fire/rescue.

Textron Marine has manufactured seven different SESs since 1971. One of them, the SES-100B, has set a speed record approaching 100 knots per hour. Textron Marine also has manufactured ten different ACVs since 1963. One of them, the LCAC, has been used in major U.S. military actions, such as the Persian Gulf War and Somalia. Enlisted personnel can be trained to operate the vehicles, which can carry seventy-five tons at fifty kph. They are powered by two 4000 horsepower engines. Seventeen were deployed and remained 100% operational during Operation Desert Storm. Three operated for over 600 hours in two months in Somalia, which is equal to twice the operation of a normal 6-month deployment.

Textron Marine Systems Shipyard Operations are located about twenty miles east of New Orleans. The facility covers twenty-five acres. All manufacturing and assembly takes place inside a 280,000 feet building. Being able to work inside makes for better welding, e.g., no sand or dirt, and guarantees that employees will not lose work-time due to unfavorable weather conditions. Seven hundred people are employed at the facility, including 500 hourly non-unionized employees. Approximately 300 employees work days and 200 work nights.

The manufacturing process consists of fabrication and assembly. Fabrication consists primarily of plasma cutting of aluminum sheets for the ship's hull to tolerances of 30,000th of an inch, and welding with a two-axis welder and robot welder, which were designed in-house. The major components that fit on the hulls are modules that are fully outfitted and inspected prior to assembly. About five weeks are required for complete fabrication and full assembly of a ship.

A key element of Textron Marine's strategy for manufacturing excellence is the use of manufacturing improvement teams (MITs), which meet every two weeks to discuss work-related issues. Each MIT is headed by a foreman and includes two or three hourly employees who rotate between meetings. Safety is always discussed first. Employees are strongly encouraged to provide feedback on any work-related issue. Information on progress/performance is distributed regularly in an easily interpreted format. Other elements of the company's strategy for manufacturing excellence include efforts by manufacturing engineers to simplify work instructions. Also included are efforts to control accuracy of manufacturing processes, such as minimizing distortions and buckling of metals. Manufacturing is involved early in design phases to lower initial cost and improve product producibility. All functions participate in product development teams to reduce throughput times.

Textron Marine uses a pre-employment craft training program to select and train prospective employees. Potential hires must attend two hour classes twice per week for four weeks (a total of 16 weeks) on their own time. If they qualify after training, they will be hired. The training is intense and includes blueprint reading, shop math, marine terminology, and a tour of the facility. About 75% of those who complete the training program are hired. Eighty-two percent of all new hires in 1993 were from the program. About 60% of the current work force were recruited from the program. The age of the average recruit is mid-thirties.

There are only three job classifications at the facility. Average hourly rates are above non-union hourly rates in the area, but less than union rates. All hourly and salaried manufacturing personnel punch a time card. Voluntary and involuntary turnover is about 12% per year. Nine percent of employees are women (some are welders and ship fitters) and 19% are minorities.

Welding is a key skill required in this facility and training to develop this skill is intensive. There is a critical shortage of skilled welders in the New Orleans area. Welders are cross-trained, so that they can perform electrical work, ship fitting and hydraulic installation. Training is conducted on a worker's personal time for 16 hours a week. It takes approximately 300 hours to be qualified and certified for welding thin materials, etc. to military specifications. Pay is increased after completion of the program, and benefits are well above the industry average. More than half of the current welders are products of the training program.

There is no quality department inspection on detail fabrication/assembly orders. Employees are empowered to inspect their own work for quality and to accept or reject it. There has been a 55% reduction is mandatory quality control inspections since 1982.

The performance results from Textron Marine System's strategy for manufacturing excellence are that all units are delivered on or ahead of schedule. The craft completion rate has dropped from ten to five weeks. The recordable and lost time accident frequency rate is 88% and 97% below the industry average. The rework rate has dropped from 2.8% to .41%. Finally, their learning or improvement curve is approximately 78%.

Using Cross-functional Teams To Cut Software Development Time

Michael Salach and Allen Reed
Modicon, Inc.

Modicon began designing and manufacturing industrial automation equipment, e.g., programmable logic controllers or PLCs, in 1968. The company was acquired by Gould in 1977 and sold to AEG/Daimler-Benz in 1988. Modicon sales are currently at $300-350 million. It is located thirty miles north of Boston in Andover, Massachusetts, and employs 1900 people who are divided equally between the United States and Europe. Daimler-Benz employs 150,000 people worldwide and has annual sales of $40 billion. AEG is one of four major Daimler Benz businesses with annual sales of $7 billion.

Mike described Modicon in 1988 as a reactive company that produced primarily "me-too" products. It was more innovative when it was a new, emerging company. Modicon had produced PLCs for the high-end of the market, but the market was growing more at the low-end. The Japanese (Omron, Mitsubishi) already had entered this end of the market, and Modicon did not want to cede this to them. The company was committed to revitalizing itself to meet the new competitive challenge. Ford Motor Company, a major customer, was a catalyst for change by involving Modicon as a supplier partner. Ford visited Modicon and trained employees in TQM techniques. Modicon also visited Crosby and Motorola. The company made quality a strategic objective and hired a Vice President for Quality in 1990. The idea was to embed quality in the business strategy. Quality and Human Resources were integrated into a single function. Responsibility for training and development was centralized and 1% of revenues was allocated to these activities. Modicon was certified for ISO 9000 in 1992. It has applied for the Baldrige Award and was a finalist for the Massachusetts State Quality Award in 1993. Mike believes that applying for such awards is a valuable learning experience because of the excellent advice Modicon receives from award examiners.

Modicon wanted to increase horizontal linkages and interactions within its organizational structure, and recognized that its culture needed to change to accomplish this. Management believed that the best way to change the way people think, talk and behave is to develop teams at all levels. Such teams were developed first within the sales force, serving as a basis for incentives for sales personnel within the same region. They now have been extended to product development and manufacturing. The company has consolidated some functions into "competency centers," e.g., sales and service, order entry and manufacturing, repair and manufacturing. Mike reviewed the "groaning pains" that the company has experienced with implementing change. In particular, he commented about the need to make sure that a team has a mission and a problem to solve. Also, process and structure need to be balanced, and assessments made periodically to assure that the direction in which the company wants to move remains clear.

Al reviewed Modicon's transition to concurrent engineering, which it now calls concurrent development because of its increased scope. The catalyst was the decision to develop a new product at the low-end of the market. The option to buy the product from an OEM was considered, but rejected. A twenty-three member team was established that included all functional departments. The team members received design for manufacturability training from Motorola. Also, they mapped the "as-is" development process and created a "should be" process from which to operate. They were guided by two overriding objectives:

(1) reduce cycle time by 65%, and (2) improve product quality of the first unit delivered by a factor of 10.

Product designers still performed design reviews, but involving purchasing at the front-end of the development process allowed parts that required long lead-times to be ordered long before the final design review. Manufacturing also could bring cost related issues into the front-end of the development process. Team members became more active in seeking input from customers to find out what this market segment needed. They were empowered to change processes that did not support the concurrent development process. Their development plan included initiatives to utilize the fewest and highest yielding manufacturing processes, utilize common components to lower the cost on this product and others through volume purchases. They planned to develop closer relationships with a fewer number of suppliers. Al showed data indicating that the average cycle time for developing new products has been reduced from 30 months to 10 months.

Product managers facilitate between the team members, but the latter also report to functional homes. The front-end of the process still has formal aspects to it. For example, the team members develop a contract book that requires sign-off by the president and vice president. The contract book requires a business plan, profit and loss projections, reporting procedures and metrics. Teams stay together through product launch and long enough to review field performance of the product, which is about eighteen months. A team could get a new charter and stay together, but the intent is that a team have a finite life and not become an end in itself.

Use of Kaizen Teams to Solve "Fit" Problems Between Complex Product Parts

Eric Smith
Sikorsky Helicopter

Sikorsky Helicopter was founded in 1923 by Igor Sikorsky. The company is owned by United Technologies and is based in Stratford, Connecticut. Sikorsky's sales in 1993 were $2 billion and are expected to reach $2.3 billion in 1994. The product mix is currently 65% military and 35% commercial. Military conversion should lead to a mirror image of this mix soon. Sikorsky currently employs 11,000 people, but expectations are for downsizing to 9,000 by 1995. The company has produced 4,000 Blackhawk helicopters, which is its main military product, plus derivatives that vary by mission, e.g., Naval Hawk or by customer, e.g., international. The Blackhawk is expected to be phased out by 1997. Prototypes are currently being built of an all composite attack helicopter, the Commanche, which will be introduced in 1999. The company's commercial products currently include the S76 and, in the future, the sixteen passenger S92, both of which are designed primarily for off-shore oil drilling.

Kaizen teams started in the Manufacturing Engineering Department after the arrival two years ago of the new director, Mike Marchitto. The department has 450 employees, with responsibility for manufacturing process planning and control as well as for tool design. The department has four departments; composites, airframe, design, and test. Communication within these departments was good, but little or no communication existed between departments. Relationships between the departments could be characterized as "throw it over the wall" and "put out fires" rather than eliminate problems at their source.

The principles that guide Kaizen, which is a Japanese word meaning continuous improvement, are to use cross-functional teams, focus on processes rather than outcomes, and be open-minded about problem definitions and solutions. Teams also need to be empowered to make changes and must receive management support with tools and systems. The structure for implementing Kaizen teams was to have supervisors select a team leader from one of the four departments, and then have the two jointly select appropriate team members from as many departments as appropriate to the problem. The problems were identified from experience on the shop-floor or from a data-base that tracks repeated defects. If the latter reaches a threshold percentage, then the problem is flagged for problem-solving. The Quality Management Board made up of senior managers meets once a week and reviews proposals to form teams to solve problems. If the QMB is not immediately sure about the merits of forming a team, the team is permitted to collect data for two weeks and submit preliminary findings to the board.

A facilitator guides team members through two hours of initial training in how to implement the five Kaizen problem-solving steps. The first step is to map the current process. The second step is to search for non-value added processes and collect and observe data where the work is performed (called "Gemba" in Japanese). The third step involves analyzing data with tools such as linear programming, critical path, and simulation, and elimination of waste (called "Muda" in Japanese). The fourth step is to evaluate results and, if necessary, to return to the second step and reiterate the process. The fifth step is to review the data, take appropriate action, and standardize the implementation process.

The first major problem attacked with Kaizen was the composite nose door of the Blackhawk helicopter which covered sensitive avionics and control boxes. If water were to seep inside the cavity, the consequences could be catastrophic. The Composite Department made the composite door, and the Air Frame Department made the sheet metal air frame. Each did a good job on their respective product, but the doors did not fit properly. At final assembly, hourly workers would trim the doors with a grinding wheel to make them fit properly. The latter improvisation was not brought to the attention of the Manufacturing Engineering Department. A government audit showed that the doors were not interchangeable between helicopters as was required by specifications. A cross-functional team consisting of Composite and Air Frame members and hourly workers made the doors interchangeable within three months. Defects have dropped to zero.

Another team was formed to work on a composite part for the 53 ESL helicopter engine. The team leader continues to track the number of defects per month. Yet another team was formed to work on the SME 6C helicopter engine inlet door, which demanded very tight tolerances. The team realized that it could not achieve the required tolerances with existing composite tooling technology (circa 1976), so it requested that it be allowed to redesign the door and use updated technology. The team membership was expanded to include designers. The door was redesigned and a prototype developed within four months. The result was a 30% reduction in weight and a 30% reduction in unit cost due to use of design for manufacturability techniques. The initial $250,000 investment had a one and a half year payback.

Kaizen teams have spread throughout the Manufacturing Engineering Department and are beginning to appear in other parts of the company. The authority of teams has been expanded to allow team members to commit as much as $70,000 for tool orders. The Kaizen initiative has produced clear-cut benefits. There has been a shift from fire-fighting to continuous process improvement. By focusing on long lead-time items, overall project lead-time has shrunk from 20 months to 15 months. Parts have become cheaper and are interchangeable. Sikorsky is now using its newly developed capability to sell some parts outside of the company.

Winning The Race To Develop A Super Efficient and "Ozone Friendly" Refrigerator

Phyllis Wooley
Whirlpool Corporation

Phyllis described Whirlpool's successful pursuit of the $30 million SERP (Super Efficient Refrigerator Program) award, which was offered by a consortium of twenty-four Eastern, Western and Midwestern public utilities. These public utilities supported the design and manufacture of an efficient and ozone-friendly refrigerator because they considered it more profitable in the long-run to lower demand for electricity than to build new plants. Refrigerators currently consume about 20% of the average household's monthly electric bill. The $30 million was to be received in the form of a $100 rebate paid per refrigerator sold within the territories of the utilities that supported the program. The winner had to sell 250,000 units within three and a half years. The scoring system for determining the winner was 75% for the product and technology, 21% for a system that tracked sales from factory to households within SERP territories, and 4% for a marketing plan to sell 250,000 units.

Whirlpool weighed the pros and cons of pursuing the award. On the con side, Whirlpool's 1993 models already consumed only 33% of the electricity of its 1972 models, and its 22 cu. ft. side-by-side model was close to meeting the SERP target with CFC refrigerants. Meeting the SERP target would require switching to a non-CFC refrigerant (HFC-134A) and non-CFC foam insulation (R-141B). A non-CFC-based refrigerator would be initially less efficient than a CFC-based one, so trade-offs would have to be made elsewhere in the design to meet the SERP target. While a great deal was known about compressors that used CFCs, very little was known about those that used non-CFCs. If problems with non-CFC-based compressors were to develop in the field, it would be expensive to remedy them. Nine months remained before bids were to be submitted. On the pro side, Whirlpool would benefit greatly from the public relations that would result from an enhanced reputation for social responsibility and environmental consciousness. Whirlpool also would benefit from the knowledge and experience it would gain from developing the product. It would be ahead of the competition in developing non-CFC-based appliances, which were mandated by the federal government by 1996.

Whirlpool formed three cross-functional teams that each consisted of ten to twelve persons. Each functional representative headed a sub-team. The Golden Carrot Task Force, which was formed in March 1992, was given the responsibility to develop the strategy for the project, identify needed resources, prepare the bid, and maintain a liaison with the SERP committee.

The Prototype and Project Team consisted of engineers, planners, accountants, lawyers, etc. from the U.S., Latin America, and Europe. The research, development and engineering personnel were from Benton Harbor, Michigan; the refrigerator manufacturing personnel were from Fort Smith, Arkansas and Evansville, Indiana; the compressor manufacturing personnel were from Brazil; and the insulation personnel were from Europe. Video conferencing was used extensively for communication. The first prototypes were developed and ready for lab testing in December 1992. The team made incremental improvements in technologies that Whirlpool already had in a state of advanced development, i.e., fuzzy logic for defrosting, thicker door insulation, high efficiency compressor and compressor fan. The result was the development of a refrigerator that was 29% more efficient than 1993 models. This refrigerator uses no more electricity per year than does a 75 watt light bulb!

A third cross-functional team was formed to develop the Exact Tracking Program for marketing and tracking sales of products by SERP retailers so that rebates claimed could be processed. SERP dealers had to be trained and supplied with literature. SERP refrigerators were to sell for the same price as non-SERP refrigerators, but dealers would receive a $100 rebate when a SERP refrigerator was sold. Whirlpool submitted its bid to SERP in October 1992. In December 1992, Whirlpool and Frigidaire were announced as semi-finalists. In June 1993, Whirlpool was declared the winner of the award. In February 1994, the first 22 cu. ft. side-by-side SERP refrigerator rolled off the production line in Fort Smith. The same SERP and non-SERP refrigerator models will be produced in parallel at the Fort Smith plant. Whirlpool plans to produce only non-CFC-based refrigerators by 1995, which is a year ahead of the mandated federal deadline.

The SERP project helped Whirlpool to refine and develop further the structure and management of cross-functional teams, such as what higher level teams should do, what the appropriate composition of teams at various levels should be, and how projects should differ depending on the magnitude of the effort to be undertaken. This knowledge will be used in developing products for Asian and Latin American markets as well as for those in the U.S.

Product Development Team Effectiveness

Gerry Susman
Penn State

An implicit assumption underlying this presentation is that the new product development process is information intensive, in that information in the form of ideas and knowledge is converted into saleable products. Viewing information as "raw material" or "throughput" allows analogies with JIT and recognition of similarities with recent innovations that have reduced cost and lead-time on the factory floor.

No matter how the product development process is organized and managed, it will always function better when it can process simpler and less ambiguous information. Tools and techniques like design for assembly simplify information by reducing the number of parts in a product, simplifying the interfaces between parts and generally making the parts easier to assemble manually or by automation. Dick Bradyhouse of Black & Decker has used Boothroyd and Dewhurst's design for assembly methodology to simplify the design of a finishing sander base. The finishing sander base initially had 23 parts that performed seven functions. The redesigned sander base has five parts that perform six functions. The redesigned sander base thus has 18 fewer parts; assembly time was reduced from 80.7 seconds to 20.8 seconds and assembly costs were reduced from 32.3 cents to 8.3 cents. Only 12% of these savings were needed to pay for the upgraded materials now being used in the product.

Information also can be simplified by designing whole families of products that can be derived from a single product platform. The families share common parts that don't have to be redesigned whenever a new product is developed from the platform. The common parts between products in the same family can be as high as 60% or 70%. Xerox's highly successful 9900 Series shared about this percentage of parts with its predecessor product. Susan Sanderson and Vic Uzumeri of Rennselaer Polytechnic Institute wrote recently how Sony developed as many as 180 different products from only three basic platforms. Each platform was developed to serve very different types of markets. The products produced from these platforms are designed to meet the needs of market niches around the world.

Information can be simplified by modularizing a product's subsystems. If each subsystem is designed to be self-contained with a standard interface between them, then several development options are available. For example, each modularized subsystem can be worked on independently so that two or more modules can be designed simultaneously. Innovations in any one subsystem need not lead to the redesign of other subsystems as long as the interface between the subsystems remains the same. Personal computers are usually designed in this way so that innovations in storage devices or monitors, for example, can be quickly incorporated into the current product. Modularity is not cost-free, however. Interface connections add costs to a product, but the benefits in development speed and market responsiveness tend to make up for the cost.

Only proven technologies should be introduced into products and introduced serially so as not to overwhelm the information processing capability of the product development process. The temptation to "hit a home run" with a new product can lead a product development team into adding too much technical risk into the new product. A product that fails to function properly after it is released to the market may never recover its reputation even if the new technology is ultimately mastered. The uncertainty introduced during the development process can also complicate problem-solving and lead to unacceptable delays in product introduction.

Codification and computerization of manufacturing data and design guidelines can simplify and clarify information that is used by project personnel, while the ability to codify and computerize such data depends, in part, on successfully completing some of the actions that were cited previously. Surveys conducted at Penn State suggest that too often relevant data and guidelines still reside only in the heads of experienced manufacturing and design engineers or can be found only in engineering handbooks on shelves. The success of many types of product development projects depends heavily on the degree to which such data is codified and accessible to project personnel.

It is very important to start each project with a clear product definition. Kim Clark of Harvard has written about the importance of both internal and external product integrity. Internal product integrity is based on the fit among all functional contributors to the product, while external product integrity refers to congruence between the product and its market, e.g., the customer's intended use for the product, customer's life style, etc. Quality Function Deployment is a very useful tool to facilitate the development of both internal and external integrity. Also, an influential concept champion can remind project personnel to keep their problem-solving consistent with the agreed-upon product definition.

Gerry showed a model that can help to understand better the types of coordination mechanisms that are appropriate to different types of product development projects. The model predicts that three categories of organizational factors affect product development outcomes such as development cost, quality, lead-time and performance. The first category, integrative mechanisms, includes organization-wide policies and practices that are designed to overcome the potentially negative effects of functional specialization. Although functional specialization is desirable for many projects, it can lead to misunderstanding and conflict between project personnel. Integrative mechanisms to discourage such dynamics include status parity between functions, strong program managers, project-based evaluation, rotation between functions, top management support and co-location of design and manufacturing personnel.

The second category, group processes, are specific practices and behaviors of project managers or team members that affect work team structure and dynamics. Examples include consensus of project goals, time spent in meetings, integrative problem-solving, percent time spent on the project, and turnover of project personnel. The third category, codification and computerization, consists of manufacturing data and design guidelines that are used to integrate product and process design. Projects vary in the extent to which such data and guidelines are codified and accessible to project team members as well as applicable to other projects being undertaken in the company.

The model assumes that group process and codification/computerization are alternate means for processing information that project members need to integrate design and manufacturing criteria. The model also assumes that integrative mechanisms have an independent and positive effect on project outcomes as well as facilitate effective group processes. Finally, the model assumes that group processes offer more effective means to process information when technical risk is high and that codification/computerization offers more effective means to process information when technical risk is low.

Questionnaire data were collected from over 100 product development projects and were analyzed by product type, i.e., "first-of-a-kind" versus enhancements, and by project outcome, i.e., cost, quality, lead-time and performance. These types of projects also differed significantly on an independent measure of technical risk. For first-of-a-kind projects, there were six significant relationships between integrative mechanisms and project outcomes. All six relationships were in the predicted direction (three involved project-based evaluation). There were five significant relationships between codification and computerization of data and project outcomes, but four of them were in the opposite direction of predictions. This pattern of results suggests that integrative mechanisms contribute positively to project outcomes for first-of-a-kind projects, while codification and computerization appear counterproductive.

For routine enhancements, integrative mechanisms only had three significant relationships to project outcomes and two of them were the opposite of predictions; in other words, the relationships were negative. For codification and computerization, four out of five significant relationships with outcomes were in the predicted direction, suggesting that routine product enhancement projects benefit from codification and computerization of data. These results also suggest that strong project managers may not be needed for such projects. Codification and computerization may provide a sufficient medium for cross-functional coordination. The evidence from this study suggests that no single coordination mechanism is right for all projects. The right mechanism depends on the nature of the project and on the type of information the project has to process.

Most studies are snapshots of a cross-section of current projects, but how companies learn to improve performance over successive projects will be an increasingly important factor for competitive advantage. Continuous improvement or Kaizen will need to be applied to the product development process with the same vigor as it is being applied to manufacturing.

The data from the model discussed previously suggests the need for project teams to diagnose their coordination mechanisms to see if they are appropriate for the kind of products they are developing. Underlying all the remaining suggestions that have been made is an attitude that will encourage people to reflect on what they are doing so that they can learn from their experiences, share information and revisit old problems. Most project personnel are anxious to move on to the next project, so they tend to devote little time to reflecting back on what went right and wrong on their last project. There is seldom any documentation available that members of future projects can use to avoid making the same mistakes as their predecessors. By contrast, Hitachi keeps "problem logs" in which problems and solutions are recorded and made available to present and future project personnel.

The manner in which senior management assigns project personnel to projects often fails to take advantage of learning opportunities. There clearly is benefit to having designers remain assigned to their projects until pilot production, yet designers are often reassigned to new projects as soon as their drawings are released to manufacturing. There also is clear benefit to assigning designers to work on derivative products within the same product family, yet too often the reassignment is based on criteria that do not take learning into account.

A substantial portion of the Japanese advantage in development lead-time for new cars is based on the speed with which prototypes are developed. This speed is due in part to the involvement of key suppliers in the product development process, which reduces bureaucratic slip-ups and delays. As a result, the same or more prototype cycles are possible earlier in the development process, permitting more opportunities to improve the product when it is less expensive to do so.

Prototyping capability also contributed to the success of Motorola's Bandit pager. The Bandit development team generated four prototype cycles during the product's development, with integration between functions being a key team objective from the start. Typically, the first prototype is monopolized by design engineering for performance testing purposes. But, in Motorola's case, every function was involved from the beginning and was expected to have an input into the prototype's development. Prototypes were scheduled by the calendar rather than by completion of development phases. Each function was expected to make contributions to every prototype cycle or to document what remained for it to contribute to the next cycle and when it expected its contributions to be ready. The generation of four prototype cycles increased opportunities to improve the final product and increased awareness among team members of each function's contributions to the development process. Obviously, "periodic prototyping" works best when the cost per prototype is low. It is less applicable to products like airplanes or locomotives, for example. Yet with advances in computer-aided engineering, we soon might see a similar process undertaken among networked team members who will contribute and react to "virtual" or simulated prototypes.

The type of learning discussed thus far is learning by doing, that is, learning from the experience of designing and developing products. Learning opportunities should not be overlooked to listen carefully to customers who use the product, either the pre-production units that are shipped to "beta-sites" or units of the first generation of the product. The knowledge gained from "learning by using" can be incorporated into subsequent production runs or into the next generation of the product. Lastly, one cannot overlook the learning opportunities that arise even from failed products. The engineering literature is replete with examples of companies that introduced an unsuccessful product, but acquired capabilities from their development experience and gathered sufficient intelligence from the marketplace to produce remarkably successful successor products.