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The Telemetry Agile Manufacturing Effort

Kansas City Division

K. D. Brown

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AlliedSignal Inc.
Kansas City Division
P. O. Box 419159
Kansas City, Missouri
64141-6159

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K. D. Brown

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The <u>T</u>elemetry <u>A</u>gile <u>M</u>anufacturing <u>E</u>ffort

By K. D. Brown

Abstract

The Telemetry Agile Manufacturing Effort (TAME) is an agile enterprising demonstration sponsored by the U. S. Department of Energy (DOE). The project was planned and implemented jointly by Sandia National Laboratory, Livermore, CA (SNL/CA), and AlliedSignal Inc., Kansas City Division (KCD)*. The project experimented with new approaches to product realization and assessed their impacts on performance, cost, flowtime, and agility. The purpose of the project was to design the electrical and mechanical features of an integrated telemetry processor, establish the manufacturing processes, and produce an initial production lot of two to six units. This paper outlines the major methodologies utilized by the TAME, describes the accomplishments that can be attributed to each methodology, and finally, examines the lessons learned and explores the opportunities for improvement associated with the overall effort. The areas for improvement are discussed relative to an ideal vision of the future for agile enterprises. By the end of the experiment, the TAME reduced production flowtime by approximately 50% and life cycle cost by more than 30%. Product performance was improved compared with conventional DOE production approaches.

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PROJECT MISSION AND GOALS

The mission of the TAME was to demonstrate agile enterprising techniques during the "product realization" of an integrated telemetry processor (ITP) using total quality principles.

The goals of the TAME were to realize a qualifiable design that implements several agile enterprising characteristics into the production process and to satisfy customer requirements cost effectively in 12 months.

The objectives of the project included the following:

- Identify and understand all requirements,
- Design to all requirements,
- Manufacture two to six units under the new design,
- Document the design definition,
- Verify and document that the product meets the design intent,
- Validate and document that the process capability is adequate,
- Accomplish the production in 12 months,
- Accomplish the production in a cost-effective manner,
- Contribute to the development of an agile infrastructure, and
- Publish a report on the results of the TAME.

The scope of the project included the realization of a qualifiable product and processes that conform to the philosophies of multifunctional production teams and distributed qualification. The product drawings were not to be released but would be accessible by the entire product realization team (PRT) from all locations. Environmental testing would not be included in the realization, but some vibration analysis would be included. The realization would not include a final development report, a production tester design, or an approved qualification release within the 12-month effort.

PROJECT INCEPTION

The TAME started in February 1993 with a planning meeting between the KCD and SNL/CA. This meeting produced an informal agreement to work together, including action to seek funding and assign resources. Shortly afterward, a multifunctional core team was created. The team established a project charter and a project plan and also promptly performed a Quality Functional Deployment (QFD) analysis. The team began conceptual design of the product in March and soon turned its attention to the issues of component procurement, product conceptual design requirements, CAD/CAM infrastructure, communication infrastructure, and qualification requirements.

The detailed design of the product began in June with schematic capture and simulation performed in Livermore. During this period the team also focused on process conceptual design and the issues associated with manufacturing. The physical layout of printed circuit boards began in July and was performed by Sandia National Laboratory, Albuquerque (SNL/NM). The production of PWAs began in September at KCD. The PWAs were shipped to SNL/CA by October for final testing and assembly. Documentation, qualification, and final assembly production and testing were completed during the final months of 1993. A close-out meeting was held late in February 1994.

The methodologies utilized in the realization of the ITP were based on Concurrent Enterprising and Design for Manufacturing principles. The project utilized both hard and soft tools that could be harnessed to improve the production process for the ITP. They included tools and methodologies for customer focus, optimized product and process design, and improvement of how people work together.

PROJECT ANALYSIS AND OBSERVATIONS

Business Systems and Culture

Business systems existed inside and outside of the project team's circle of influence. Systems outside of the production team include support organizations such as accounting, purchasing, legal, program management, marketing, and information systems. Systems within the production team included organizations such as system product and process engineering, test equipment engineering, quality engineering, and manufacturing.

Culture is considered to be how people interact, norms associated with the environment, and individual behavior. The TAME was not formally chartered to change culture or business systems outside of itself except through informal relationships. This was accomplished by cooperative approaches including identifying representation from outside organizations, introducing them to the TAME, and negotiating win/win strategies. In some cases this approach worked well; in others it took a significant amount of time to evaluate risk, negotiate for resources, or obtain authorization.

The TAME quality requirements stressed many existing business systems and cultural norms. Short flowtimes associated with the compressed schedule often were in conflict with the traditional production systems. Costs associated with mass production approaches were in conflict with the small lot quantities and unique requirements for customization on the TAME. The management of risk necessary to do things differently and the empowerment of the team to be innovative and creative were in conflict with many traditional management systems.

Therefore, the TAME challenged the status quo of the present business and cultural systems for production.

The lesson learned about business culture is that risk taking and experimentation are limited. Trying new approaches to old problems is not encouraged because it involves unknowns and increases risk. Creative innovation is not encouraged in this environment because people are fearful of failure. There is very little incentive to team, share information, and help other people to be successful. Therefore, people limit information and have an individual perspective. Recognition and reward systems are not consistent with the formation of teams and the success of teams. Improvements need to be made in the reward and recognition systems to provide incentive and recognition of teams and team players. Training to overcome individualism is necessary in order for people to support the concept of teaming. Also, fear must be driven out to encourage creativity and innovation.

Improvements can be made by fostering an environment where individuals are respectful of others' ideas. The ability to listen and articulate ideas is critical to the success of teaming. A culture that nourishes and rewards rich personal relationships and interpersonal skills is important. This is necessary to develop the trust of others on the team. Performance objectives and reward systems should reflect this environment.

Business Systems

This effort showed that business systems are often control oriented and not entrepreneurial. They employ control at the top by limiting distribution of information and authority. This has the effect of limiting power and decision making at the working level of the organization. This prevents the working level individuals, who are aware of the benefits and cost aspects of new opportunities, from creating and maintaining new partnerships. When they pass along information about new opportunities or necessary improvement changes, the time lag is often long enough or the energy required to build support for the idea is large enough that the opportunity has evaporated or the needed change is abandoned. Improvements are necessary to empower the working level to make entrepreneurial decisions. They need access to information and they need leadership from upper management. This will allow them to become agile in the formation of opportunities and the realization of products and processes to support the customer.

One of the major impacts the TAME had on business systems and culture was as a benchmark activity. It was observed that technology alone, without congruent business and cultural developments, will not make significant impacts in large organizations. The impacts on business systems outside of the TAME were limited, although the team was able to influence culture within the areas of product, process, quality, and test equipment engineering.

Observations in this area include improvements to performance and reduction of cost and flowtime; these were due to changes in culture within the TAME design and manufacturing phases. Gains in agility outside of TAME were limited because of small impacts on business systems.

This effort also has shown that there has been an intense concentration on technology, with a lack of focus in the areas of culture and business systems. While the group did consider culture and organizational strategies within the team, it was relatively powerless to deal with issues outside of the group. This made it difficult to obtain quick support from the management of support organizations to do things differently. There was little time to negotiate with these organizations.

Conflict occurred between the culture within the team and the culture of support organizations. The expectations, norms, and behavior differed so that the team was often frustrated by the service it received from support organizations. Despite these sentiments, the TAME did successfully influence many of these support organizations that it interacted with.

Team Structure

The TAME observed improvements based on culture changes in the structure of the team. An example of improvement based on culture change occurred when the traditional separate functions of design, development, and manufacture were considered as a unit. The stakeholders of each phase were combined in the team. Antagonism and suspicion were replaced by mutual cooperation, joint ownership, and trust. This allowed the team to synergize its efforts, allowing productivity to increase.

The trust, commitment, and rapport that the team members developed for one another was exceptional. Mutual respect, consideration, and cooperation existed throughout the project. Interpersonal communication skills and leadership were key to this culture. The roles and responsibilities that each of the team members supported were dynamic. This is not to say that the team agreed about everything. There were many heated debates about important issues, but the team strived for consensus and obtained responsible support for the issues at hand. Consensus was defined as a solution that everyone could live with, not necessarily what everyone wanted. This is largely due to the ownership and commitment the individuals had for the long-term project charter.

Component Procurement and Qualification

One example of a culture change outside the TAME was in the area of component procurement. In this case, the team developed a task group to address the problems associated with the long lead time, high cost, and high reliability components supplied by the traditional DOE system. The task group outlined a component procurement plan that was sanctioned by component quality, component engineering, purchasing, and the team. This plan allowed the team to specify the qualification and acceptance requirements for purchased electrical components. This deviated from the traditional 100% sample and test philosophy. This approach required three traditionally opposing forces to collaborate on a common goal.

These changes resulted in considerable time and cost reductions that were sufficient to make the project successful. It was observed that flowtime and cost impacts were significant with the redesign procurement process. This was related to the reduction in testing, the utilization of vendor qualification and acceptance data, and the use of commercial off-the-shelf and mil spec. components.

Areas for improvement could be made through electronic transfer of contracts, letters of intent, and customer financial agreements; tracking could be implemented to greatly improve the agileness of partnerships outside the organization. This would have the effect of reducing the energy necessary to establish partnerships and the time necessary to develop agreements. This capability should be desktop to desktop in the business area of the organization and should allow management to quickly assess, develop, and finalize partnerships.

Other improvements that were observed based on culture change were in the area of product qualification. The objective was to qualify the production system along the way in contrast with doing that at the end of the development phase. This required quality, product, and process designers to work together from the outset of the project. The design verification process changed from an antagonistic audit to a cooperative commitment and by doing so became successful for the customer.

Multifunctional Teaming

The team was multifunctional, being composed of design, manufacturing, test equipment, process, and quality engineering personnel, with support from manufacturing and management. The team was comprised of individuals that were geographically remote from each other: Livermore, CA; Kansas City, MO; and Albuquerque, NM. A core team was established and was comprised of design, product, process, and quality engineering. The core team had planning and project management responsibility.

The larger team was coordinated by the core team to accommodate the needs of the project and implement the principles of agile enterprising. Task groups were formed to accomplish elements of the effort such as robust design, design for testability, process characterization, and material procurement, among others. These task groups were coordinated by the core team in weekly video conferences that linked the remote sites. Daily E-mail and teleconferences were used by individuals to communicate the details of the project.

In the TAME, the benefits realized by using a multifunctional team were increases in quality, reduction of cost, reduction of flowtime, and increased agility for the project. These benefits can be attributed to the influence that all stakeholders exerted on the production cycle. Because firsthand knowledge was allowed as a forcing function, the outcome was optimized for more of the production cycle than would have been possible from narrow efforts.

Improvements in performance resulted because more knowledge was available in the decision-making process so that a higher fidelity solution was generated. Improvements in flowtime resulted because less mistakes are made by a team in contrast to an individual and more information is readily available in the decision process, resulting in more efficiency.

Improvements in cost are attributed to more efficiency and less waste associated with an optimized decision process.

Agility was increased for the project because the concept-to-cash flowtime decreased along with the decision-making flowtime. The team's ability to make a broader range of product and process decisions enhanced its ability to make more products at any given time.

The team was a forum for all the stakeholders to share their perspectives, requirements, and expectations. These forces helped to check errant opinions and intuitive reasoning that can grow from a single perspective or opinion. The practice of discussion and debate was important to this process because through sharing of ideas, consensus is developed in the group.

Consensus was costly in some cases because not everyone got the result that they wanted every time. The group strived to generate solutions that everyone could live with. If someone could not support the result, then more work was necessary.

Multifunctional Team Training

Common training for the team was conducted to develop a consensus, a common vocabulary, and a broader understanding of the entire production cycle. The curriculum stressed the need to understand the customer and to utilize concurrent engineering, robust design, Design for X, cost management, robust process design, process control, and other quality tools to optimize production. The core team was exposed to a four-day overview of Design for Manufacturing and Concurrent Engineering. This curriculum was not designed to cover the details of any tools or concepts, but to introduce them enough that the team could effectively pursue them in a just-in-time manner. The class helped the team to decide which tools would be appropriate for the TAME and which would not be productive. It also helped the group to develop a common understanding of what each tool could achieve.

The major benefits realized by utilizing multifunctional training are increased performance, reduced flowtime, and enhanced agility. Increased performance was derived from the implementation of new tools, concepts, and methods introduced by the training curriculum. Application of tools like QFD, robust design, or Design for X would not have been considered if the team could not understand them, agree that they were value added, and apply them as a group. Otherwise, each person would have resorted to his individual style to accomplish the tasks. This training helped the group develop a community style. Savings in flowtime can be attributed to the team's cooperation and synergy. Following the training, there was little time spent researching the tools or debating about the benefits of their application. The group decided together and moved together.

The lesson learned from the application of team training is that when all the team members have a common understanding of the purpose and benefits of quality tools and new philosophical concepts, the application and execution of such tools is possible. Otherwise, the team cannot agree on what tools to use or their application. Improvements can be made by making more value-added training available and by exposing entire teams to the same training at the beginning of a project.

Virtual Enterprising

The TAME exercised virtual enterprising to link several independent enterprises. Specific portions of KCD, SNL/NM, and SNL/CA were integrated to provide the necessary skill set to support the project. Each enterprise contributed some percentage of the total expertise, facilities, equipment, material, etc. to generate sufficient support. Integrated network links to vendors for support services such as mechanical cases and printed circuit boards were utilized to the extent possible.

The benefits of virtual enterprising were decreases in flowtime and cost, improvement of performance, and enhanced agility. Because the overall experience of the team was not confined to a single enterprise (limited perspective and experience), flowtime decreased. This allowed efficient communication of ideas. Because the group was able to negotiate priorities, costs were decreased by tradeoffs between the various enterprises. Performance was enhanced because the forces of the entire production cycle influenced the product and process design. The agility of the team was increased based on decreased decision-making time, expanded product and process decision capacity, and decreased concept-to-cash flowtime.

The virtual enterprising aspects of the TAME facilitate synergy between organizations and allow access to resources to fill gaps that single organizations may not have. The lessons learned in teaming between individuals apply also to teaming between organizations. Culture must be developed between companies that allows formation of alliances in the marketplace.

Opportunities for improvement in this area could be made if corporate policy was focused to facilitate the movement of the company into and out of virtual enterprises as the demands of partnerships change. This could include streamlining systems to communicate with outside organizations, systems to assess business opportunities, systems to generate business plans, systems to process contractual agreements, and systems to manage flexible allocations and exchanges of resources with outside organizations. This technology should allow access to corporate knowledge databases to access past approaches and shorten the flowtime for generation of new business plans.

Concurrent/Congruent Engineering

Concurrent engineering was utilized by the TAME to consider downstream processes in the front end of the design cycle. As many stakeholders as possible were included in the production process. Design-for-X (testing, cost, manufacturing, etc.) methods were utilized to optimize the design and reduce mistakes. The design team was influenced by manufacturing, test equipment, process, quality, and component engineering before the detailed design was established. The TAME project plan caused the sub-teams to vector toward a common goal despite their geographic distribution.

The benefits realized by utilizing concurrent and congruent engineering were increased performance, reduction of cost, reduction of flowtime, and enhanced agility. Product and process attributes were influenced by an entire production cycle perspective, resulting in an optimized solution. This dramatically impacts cost, flowtime, and performance. This is directly attributable to the sharing of ideas through concurrent engineering. Concurrency was enabled through the coordinated planning effort and the utilization of communication infrastructure.

Reductions in flowtime resulted because of efficiency as it related to reduced mistakes and cooperation of all the stakeholders. Many tasks were scheduled in parallel rather than in serial; because the sub-teams were coordinated and the culture contributed to sharing of information, there was very little waiting for information. Reduced cost resulted because of the efficiency gains over past approaches. Improvements in agility are based on the decreased decision-making flowtime, the decreased concept-to-cash flowtime, and the increased product and process decision capacity.

The team was able to maintain congruency throughout the project. This means that the efforts were constructive and progressed to support the overall mission of the project. This accomplishment was considerable in that the many of the tasks were geographically distributed.

The lesson learned from application of concurrent engineering is that when all the disciplines that are stakeholders in the production cycle are allowed to work on one another, the outcome is an optimized solution. This interaction forces trade-offs early in the development of a project and facilitates consensus and cooperation. Improvements can be made by developing more robust communication infrastructure to the desktop of the teams. This is necessary to implement the realtime interaction necessary for concurrency; that is, what can I do that is constructive and value added? This requires information about the intentions of the other team members so individuals can plot courses from where they are to the groups goals.

Utilizing a project plan to direct and track the progress of a project is the means to congruent activity engineering. This planning must include project vision, mission, goals, objective, and scope elements to sufficiently characterize the end point and deliverables of the project. The desire is for all activities to converge to the degree that the result is constructive. In order to make this happen, all areas of the project must be able to adapt specific plans to vector themselves from the present to the future destination. Improvements can be made in the planning of projects. It often seems unnecessary to document and agree on these elements of projects because it may be considered common knowledge, but these elements are necessary to achieve congruency.

One of the shortcomings of this project was the lack of support that the project had from the drafting and purchasing organizations. They were not introduced to the project planning or the team training. As a result, they were not as supportive of the agile requirements and tended to operate in the traditional mode. Improvements can be made by including support organizations in the planning, training, and concurrent engineering efforts so that they will have ownership and congruency in their roles.

Quality Functional Deployment

Quality Functional Deployment (QFD) was utilized to identify what the customer wanted from the project and to map those requirements to product and process requirements. First, the core team identified customer requirements by building a House of Quality for the project. The team identified its customers, identified what each customer wanted, and outlined how the team would accommodate the customer requirements. Relationships between the customer requirements and project attributes were developed to understand the interdependencies and relative importance of each project strategy.

The significant project attributes were carried forward as product design requirements for the next stage of the QFD. Product attributes were formed to accommodate the design requirements. Again, inter-relationships and importance factors for the product design were generated. The critical design attributes were carried forward as process design requirements. Process attributes were developed to accommodate the requirements, as were inter-relationships and importance ratings for manufacturing processes.

QFD reduces cost and flowtime because product and process requirements are optimized, and it improves quality because requirements are systematically captured, prioritized, and mapped in the production system. A customer-driven project plan was generated from the QFD. Product design requirements were derived from the customer requirements and priorities based on the customer's perspective. This process allowed the team to identify the critical product and process attributes. This led to a set of customer-driven, optimized goals for the project, product design, and process design phases of the project. This approach established consensus, understanding, and integration in the area of requirements.

The lessons learned from the application of QFD are that the development of customer requirements can be organized, systematized, and utilized to drive all aspects of product and process design. Opportunities for improvement in this area exist for technology that allows interactive development of customer wants. This could be accomplished by deploying systems that allow for model-based communication, with multimedia interfaces for customers and production teams.

Other improvements could be realized by developing a culture that focuses on customer-driven processes that have clear links first to product requirements and second to customer requirements. Technologies to interface with tools like QFD, knowledge-driven databases, and CAD are necessary to integrate the requirements generation function with the product and process design functions. Technology that interfaces the customer requirements function to databases of past product and process designs, project plans, etc. are necessary to reduce the reinvention of technology and facilitate rapid low-risk responses. The system should interact with expert modules to facilitate the automatic scoring of proposed approaches to customer requirements.

Multifunctional Project Planning

The core team employed a multifunctional approach to develop a project charter that identified its mission, goals, objectives, and scope. This charter was coordinated with the results of the House of Quality to validate its thoroughness. The charter was utilized in the development of a work-breakdown structure leading to a detailed project plan. With this approach, the milestones and tasks were developed out of the charter, giving the plan focus and cohesion. The plan identified a schedule and responsibility for each task. This effort resulted in a master project plan that was utilized throughout the project to track status.

The benefits of multifunctional planning were reduced flowtime and cost because of the breadth of knowledge in a multifunctional team. Improved quality was also achieved because of the improved accuracy of the multifunctional planning. This type of planning helped to build consensus throughout the project about what the goals and objectives of TAME should be. The tasks, durations, and schedules were more accurate with this approach. The credibility of the plan was increased with a consensus approach, creating more confidence, commitment, and ownership of the plan. This improved the TAME's ability to support the customer and the efficiency of the implementation phase.

The lesson learned from multifunctional planning is that this type of planning is critical to implement virtual enterprises and congruent engineering. It is the means to congruency; that is, it helps to focus the concurrent activities on a common focal point. Opportunities for improvement include deploying technologies to interactively develop project plans by geographically distributed production teams. This would allow input from individual workstations for the generation of milestones, tasks, durations, and resource requirements. This technology should allow interactive brainstorming so that project charters could be generated by these distributed teams without physical contact. This technology should also interface with the corporate knowledge database to access past approaches to similar requirements. This will shorten the time necessary to plan new projects.

Electronic Design and Communication

The TAME effort utilized networked CAD/CAM systems for the electrical and mechanical design activities. Because common applications were available between the remote team sites, information transfers among the team members did not require significant translation. An intersite link was utilized by the TAME to move information between Kansas City, Livermore, and Albuquerque. This link made the movement of electronic mail and design data fast and efficient. This link was vital to supporting concurrent engineering and implementing the virtual company.

Because the systems were networked, the transfer among the remote team members was seamless, quick, and easily accomplished. Product schematics, layouts, and mechanical models were passed from desktop to desktop in a manner of minutes. Teleconferences could be coordinated while simultaneously looking at the same design file. This capability allowed team members to concurrently participate in the design process. Access to the design information was granted to all team members so that downstream members could influence the development of the electrical and mechanical designs.

The benefits of networking CAD/CAM systems were decreased flowtime and cost. Decreased flowtime resulted because there were fewer mistakes (directly related to concurrent engineering) and because of the speed of design transfer between the team-members. Because the manufacturing equipment was seamlessly integrated with the design tools, reductions in flowtime resulted. The reduction in cost was due to the reduction of labor associated with recreating and re-entering design information.

The lessons learned in the area of networked design tools are that the interoperability, portability, and performance of CAD tools are limited. Other limitations included (1) the capability to seamlessly pass mechanical information to electrical tools, (2) the capability to seamlessly move design information to analysis tools, (3) the capability to seamlessly move information from design to manufacturing, (4) the ability to pass information from applications on different platforms, and (5) the availability and accuracy of component and part models.

Weekly video conferences were utilized by the TAME to effectively manage and track the master project plan. This capability linked the geographically distributed team during the entire production cycle. The core team would meet alone every other week, alternating with the task groups to maintain communication between the team members. Electronic mail and teleconferencing was used by the TAME to implement effective communication between the team members. Reports, data, and correspondence were transferred between the remote members quickly, easily, and effectively.

Communication can be improved by implementing a more robust E-mail application that can handle transfer of binary data attachments and desktop-to-desktop multimedia interfaces. A more open architecture infrastructure is necessary to allow transfer of information in a heterogeneous environment.

Design for Robustness/Virtual Prototyping

Design for robustness was defined for this effort as "performance is insensitive to variation." It was recognized that variation can be internal or external to the product. Internal variation includes components, pieceparts, processes, and material. External variation includes temperature, pressure, humidity, altitude, shock, and vibration. Critical product parameters identified by the QFD were analyzed over a specific range of internal and external variations. Design performance was simulated or analyzed in the presence of variation to assess sensitivity. The results were used to determine if the design was robust.

Tolerance design was also performed to optimize the requirements of the product. The tolerances were made as large as possible to minimize the cost of processes while maintaining adequate design margins to ensure performance for the customer. Design margins were defined as the difference between catastrophic failure and the worst-case product specification. The product tolerances were defined as the variation allowed from the parameter target where the degradation of product performance is tolerable. The parameter target value was defined as the ideal goal for the particular parameter. Each target value, tolerance, and design margin was documented to allow effective resolution of product performance, process requirements, and risk.

The TAME utilized simulation and analysis to the greatest extent possible. The team attempted to minimize physical prototypes to evaluate performance of the product. This approach was chosen to minimize the flowtime and cost associated with iterative design development. Simulation and analysis were utilized to predict performance of the design without the time and expense of building physical prototypes. The practice of virtual prototyping, in contrast to physical prototyping, allowed the design team to more thoroughly exercise the multidimensional solution space, producing a more robust solution. Simulation results were made available to the entire team across the network.

The benefits of robust design were reduced cost due to less nonconformance, reduced flowtime due to optimized requirements, and increased quality due to improved product performance. It is important to note that acceptable performance was considered to be more than functionality in a laboratory environment. The parameter design generated by this approach optimized the product solution space to minimize its sensitivity to internal and external variation that will be encountered by the customer. Tolerances generated by this approach were maximized to reduce process requirements while maintaining adequate design margins. Design margins were determined to maintain product performance with some margin for error and unforeseen circumstances.

The lessons learned from the application of robust design are that the state of understanding and the tools available to truly implement robust theories such as Taguchi do not exist. Advanced integrated design tools that are capable of generating virtual prototypes that accurately model physical reality are necessary. Systems such as this are critical to both the design of product and processes. In this fashion, the multidimensional solution space can be exercised, yielding design margins, targets, and tolerances that produce robust performance for products and processes. When this technology is applied to processes, it will facilitate the virtual simulation of factories, reducing the time and cost of capitalizing new enterprises. The output of the virtual factory could be compared to the ideal virtual product prototype to assess the capability of the factory before any equipment or material dollars are risked.

Technology is necessary to archive the results of design for both processes and products in the corporate database and to access past approaches, thereby reducing the need to reinvent technology. Open access to this information is necessary for the entire team to implement concurrent engineering through the sharing of information. Technology to track the work flow of the design through its states is necessary; this should allow the remotely distributed team to assess status of drawings, change issues, and approve the release of design information from one state to another.

Distributed Qualification

A distributed qualification was utilized throughout the production cycle rather than at the end of the development phase. The qualification was phased; that is, it was accomplished throughout the project. This approach identified first requirements; second, a plan to achieve the requirements; third, the verification of the results; and finally, release of the design for production. The first stage was accomplished early in the project when the preliminary requirements were developing. The second stage was accomplished while the conceptual design was developing. The third stage was supported during the detailed design segment of the production. The fourth stage will not be completed for the TAME because it is outside the scope of the project charter.

The purposes of the qualification were first to assess whether the design would meet the customer's requirements adequately and then to assess whether the manufacturing processes could adequately yield the product.

The benefits of a distributed qualification were reduced flowtime and cost due to optimized qualification requirements. The TAME also achieved improved quality because the qualification process was driven by the customer rather than an unresponsive system. This approach not only identified the requirements necessary to qualify the product, but resulted in a plan to support the requirements and data to determine whether the system would meet the requirements.

The lesson learned from the distributed qualification approach utilized by the TAME is that quality parameters can be designed into product and process as the project matures rather than at the end when change is very difficult. This is accomplished by developing the qualification requirements while developing the design requirements. Early planning to implement the requirements is essential to realizing them and drives the design team to generate the data and justifications for conformance while designing the product.

Validation of qualification requirements should be performed as the team progresses through the production cycle rather than at the end of the project to allow time to respond to problems. This tracking process focuses the design team to generate value-added information necessary to qualify product and process.

Opportunities for improvement include the development of technology to allow geographically distributed teams to interactively brainstorm requirements as the design process progresses and as plans are developed. The technology should facilitate the creation of documentation that validates the requirements and database management systems for retrieval of qualification information. Technology is necessary to allow the qualification team to access the corporate knowledge database. This access to design, past qualification, and other planning information associated with the qualification of products and processes is necessary. Technology to remotely authorize and release designs as they travel through the qualification states is necessary. This technology should allow team members to affix their signatures to qualification documents without physical contact.

Design for Testability

Design for Testability was a concept utilized to consider how the product design could be optimized to reduce the cost of design verification and production testing. Design verification testing's purpose was to validate that the design performance would satisfy design intent. Production testing's purpose was to verify that a single production unit was manufactured correctly. By separating the requirements and focusing on the production testing, the tendency to repeat the design verification testing many times in production was reduced.

A task group comprised of test equipment design and product engineering personnel studied the sources of testing cost. Several sources were identified, and strategies were developed to optimize the cost of testing for the entire production cycle.

The benefits of design for testability were decreased cost and flowtime due to optimized requirements. These accomplishments were produced by identifying testing goals and requirements and by trading off various approaches to optimize performance, cost, and flowtime of the project. Reductions in cost for production test equipment were estimated to be 37% and reductions in flowtime were estimated to be 40%.

The lesson learned by design for testability is that when the team focused on the issue of high-cost testing (with the knowledgeable individuals and the goal of optimizing an approach), they were successful. This activity is only an example of what can be accomplished with the entire Design for X (testability, robustness, reliability, cost, etc.) concept. Areas for improvement lie in the development of technology to access databases of past approaches with knowledge-driven queries to facilitate trade-off analysis and optimization of performance metrics.

Process Characterization and Control

Critical processes were identified in the QFD analysis. These processes were then characterized to identify the process inputs, outputs, and the relationships between them. This effort is to understand how to control the processes to produce the product parameters. Control systems are then put into place to produce the desired results on a consistent basis.

Process capability assessments were completed for each critical process. Process capability is determined by the ratio of the process average output minus the nearest specification limit to 3 times the standard deviation. A value of 1.67 or greater effectively places the process mean in the center of at least 3 sigma distribution, resulting in less than 0.5% rejection rate. By evaluating the process capability for each process, an objective measure of the design's manufacturability is obtained. If no capability or unacceptable capability exists, then new process development or improvements are necessary.

Process characterization and control improved quality due to understanding of critical processes and validation of process capability and control. Cost was also decreased due to the reduction of nonconformance associated with processes that have adequate capability and are under control.

The lessons learned in the area of process characterizations are that understanding process capabilities (inputs, outputs, interrelationships, variation, etc.), establishing that the capability is compatible with product requirements, and maintaining this capability impacts the quality, cost, and flowtime of product manufacturing. Identifying these elements of processes is costly and laborious and requires expertise and time; however, it is necessary to definitively assess if a system can repeatedly manufacture a product.

Project and Product Documentation

Documentation of the project requirements, design intent, design definition, and qualification data is important. Having this information in an accessible form for the current and future teams is also important. The team created a plan that outlined the requirements for documentation and tracked its status. All requirements and design intent information was included. The plan also included design analysis and simulation results. The plan also identified information to justify qualification of the design. The plan identified title, author, location, and issue for all the project and production records.

The major benefits realized by implementing project and product documentation are reduction of cost and reduction of flowtime. Cost and flowtime savings were derived from efficiency related to the location and retrieval of information associated with product design and project planning. This information will be accessible over the entire life of the product because it is documented. The information will be available to future teams that may not have participated in the development.

The lessons learned about documentation fall into two areas. The first is what information to include in a database, and the second is how to manage the database. The team learned that design intent and verification information could be captured and documented concurrently with the design phase. Information about commercial component justifications, results of parameter trade-offs, design margins, etc. were documented in design reports. Project information was recorded and included in the project file also. This included information such as project plans and communiqués among the team. All this information has been archived with descriptions and locations in a database that can be queried to search for documentation.

Material Procurement

The team developed a redesigned material procurement and qualification plan. This plan was consistent with the performance, cost, and flowtime requirements of the TAME. The plan incorporated design, component, quality, and product engineering requirements and also incorporated several novel steps to reduce cost and flowtime while maintaining performance relative to past procurement cycles for normal production.

There were three major developments. (1) Almost no electrical testing was repeated through inspection and receiving. This is in contrast to 100% testing of most regular product. Basically, the test data supplied by the vendor was utilized for acceptance. (2) In addition, vendor-supplied data was used for qualification of new vendors. Many of the vendors were already on our preferred vendor list, although a few were not. (3) Requirements were relaxed so that commercial components could be used rather than custom components. With these changes, flowtime and cost were reduced significantly while performance standards were maintained. In summary, the intent of QC1 was supported with reduced cost and flowtime.

The benefits associated with the optimized material procurement plan are reduced flowtime and cost and increased quality. Flowtime savings were derived from optimized acceptance requirements. The major flowtime savings resulted in reduced qualification plans and inspection requirements. Cost savings were derived from reduced inspection and testing. Quality was improved because the acceptance requirements were customer driven rather than system driven.

The lesson learned about the procurement of components was that performance can be maintained while flowtimes and cost are reduced. The team experienced considerable resistance to using commercial components and then to the notion that source acceptance data could be used rather than in-house testing. The traditional approach was difficult to overcome, but finally progress was made. It was shown that by combining quality, component, design, and product engineering, the right choices to be successful could be made.

Considerable effort was necessary to generate drawings and procurement packets before orders were placed with vendors. In addition, the shipping and receiving departments did not expedite material through their systems. Improvements can be made by streamlining these efforts and making the process more integrated and concurrent with the production effort. These improvements could include the use of electronic forms and electronic transfer of requirements, contracts, and drawings. Electronically integrating the location and status of material in shipping and receiving would improve the project's ability to track material leaving and arriving at the plant.

CONCLUSIONS

There were many lessons learned during the TAME project and several opportunities for improvement were noted. Lessons learned are considered to be conclusions based on observations, some of which are related to areas where performance was less than ideal. Opportunities for improvement are recommendations related to lessons learned that can move the production performance boundaries forward.

TAME benefits are measured relative to the metrics of cost, flowtime, performance, and agility. Cost, flowtime, and performance are orthodox metrics of quality and will not be elaborated on. Agility is considered to be the ability to thrive in an environment of constant and unanticipated change. It is specifically measured by metrics such as concept-to-cash flowtime, the speed of organizational decision making, the difference between the unit costs of mass production lots and prototypes, the flexibility to make any product at any time, and the degree of mass customization versus mass production that an organization can provide.

The conclusions of this study fall generally within three areas: the culture of people as they interact in an endeavor, business environment as it pertains to mass production versus agile manufacturing, and technology advances that can improve the performance of a project like the TAME.

Concerning **culture**, from each team member the job required effective interpersonal skills, a willingness to cooperate with diversity, a commitment to the agile vision, and outside-the-box thinking. The project was demanding in that it caused individuals to stretch their comfort zones and try things that were different. This paradigm shift often generated reluctance, anxiety, and resistance to change, most likely due to the fear of failure. At the same time, the project was rewarding and exciting in that the team felt empowered to determine its own destiny. The results were encouraging and served to build support for the agile philosophy within the team.

Considering the **business environment** of this project, there were several major indications that the supporting organizations were less than agile. Although the concept-to-cash flowtime was somewhat positive in this case, the speed that the organization (outside of TAME) made decisions was slow and inefficient. Decisions often required lengthy consultation and several layers of management approval prior to finalization. These decisions were often related to resource allocation or to approval for trying a novel approach. Flexibility to accomplish work outside the normal mode of operation was limited by policy, procedure, and hierarchical control.

Although the life cycle costs of the project decreased, there still remains a large difference between small lot and mass production unit costs for this project. In this case, the nonrecurring costs are significant and cannot be hidden in the unit price of large quantities. This forces the customer to carry significant tooling and start-up costs. This is because existing production processes are not flexible enough to accommodate new product requirements without major changes. This in turn is due to configuration and programmability limitations of existing production processes.

Highlighted in this experiment was the limitation of existing processes to make "any product at any time." The team learned that there are limitations to the organization's ability to form virtual enterprises, form teams, and manage flexible resources. This has the effect of limiting the availability of expertise, knowledge, and manufacturing capacity to realize this goal.

Finally, the experiment revealed that our companies have an orientation to mass production rather than mass customization. Mass production achieves its benefits from economies of scale derived from products that embody the statistical norms that society will purchase. In contrast, mass customization achieves its benefits by producing one-of-a-kind products that appeal to a single customer. The underlying system for each of these types of production is different. The former relies on standards and control to a specific target where speed and large quantities lower unit costs. The latter redefines a product as a platform for upgrades, defines a customer as a subscriber, and defines a supplier as a partner. The former asks the customer to compromise to a set of specifications or standards to save cost and time, while the latter is flexible enough to accommodate exactly what the customer wants while maintaining cost performance. This team worked together to customize the appeal of its products to the individual. Through flexibility and synergistic leveraging, the team lowered costs and flowtime.

In the area of **technology advances**, development of advanced design tools for virtual prototyping of products and processes is needed. These tools provide the capability to optimize products and processes concurrently through integrated functions like modeling, simulation, analysis, and requirements management.

To facilitate integration of the enterprise, development of an advanced concurrency infrastructure is necessary. This infrastructure should provide three dimensions of integration. First, it should integrate the human element of the team; second, it should integrate the tools of the team; and third, it should integrate the product realization environment of the team. These dimensions must be extensible across enterprise and organizational boundaries.

To minimize the reinvention of technology and make the fullest use of past experience, development of an advanced historical database system is necessary. The team did not have ready access to past history on this type of effort. This was an obstacle because the team did not have any reference with which to compare its plans. This meant that there was always some degree of risk associated with new approaches. An opportunity for improvement exists in the formation of a distributed corporate knowledge database. This database could be distributed across the entire production team and could serve to archive past project information. This database could be used to collect data such as project planning, troubleshooting, quality history, procurement information, design intent, manufacturing rules, and design guides. In short, it would become a large repository for the entire production cycle and would provide reference data for future projects.

In closing, the TAME is considered to be successful relative to its mission—as a benchmark of the existing production system and for generating data for improvement. Several important accomplishments from this effort should be noted:

- The TAME designed and manufactured six qualified printed wiring assemblies and a mechanical housing in 13 months.
- Overall, the project posted an estimated development cost reduction of greater than 30% and a development flowtime reduction of greater than 50%.
- Performance was increased many times compared to prior approaches.
- The design performance is considered to surpass any system generated prior to this time.