A Review of the Technologies Enabling Agile Manufacturing Program*

W. H. Gray
Oak Ridge National Laboratory
Bldg. 4500N, Mail Stop 6203
Oak Ridge, TN, 37830-2008, USA
p:(423)574-1476
f:(423)241-6649
whg@ornl.gov

R. E. Neal
Oak Ridge Centers for Manufacturing Technology
Bldg. 9201-3, Mail Stop 8068
Oak Ridge, TN 37830-2009, USA
p:(423)574-1862
f:(423)576-4663
nea@ornl.gov

C. K. Cobb
Lockheed Martin Energy Systems
Bldg. 9103, Mail Stop 8160
Oak Ridge, TN, 37830-2009, USA
p:(423)576-1884
f:(423)574-4748
cli@ornl.gov

* Sponsored by the U.S. Department of Energy and the Center for Computational Sciences of the Oak Ridge National Laboratory under contract DE-AC05-96OR22464 with Lockheed Martin Energy Research Corporation.

The submitted manuscript has been authored by a contractor of U.S. Government under contract no. DE-AC05-96OR22464. Accordingly, the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes.
DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.
DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.
Abstract
Addressing a technical plan developed in consideration with major U.S. manufacturers, software and hardware providers, and government representatives, the Technologies Enabling Agile Manufacturing (TEAM) program is leveraging the expertise and resources of industry, universities, and federal agencies to develop, integrate, and deploy leap-ahead manufacturing technologies. One of the TEAM program's goals is to transition products from design to production faster, more efficiently, and at less cost. TEAM's technology development strategy also provides all participants with early experience in establishing and working within an electronic enterprise that includes access to high-speed networks and high-performance computing and storage systems. The TEAM program uses the cross-cutting tools it collects, develops, and integrates to demonstrate and deploy agile manufacturing capabilities for three high-priority processes identified by industry - material removal, sheet metal forming, and electro-mechanical assembly. This paper reviews the current status of the TEAM program with special emphasis upon TEAM's information infrastructure.

Keywords
Computer aided design, computer aided manufacturing, agile manufacturing, computer simulation, expert systems, enterprise integration, virtual enterprises

1 INTRODUCTION

In July 1994, the TEAM (Neal, 1995) program began the execution of a strategic and technical plan collaboratively designed by private industry and U.S. Department of Energy (DOE) facilities in the arena of agile manufacturing (Goldman, Nagel, Preiss, 1995) technologies. For years the DOE National Laboratories and production facilities have operated as a distributed enterprise for development and production of complex products with stringent performance and quality requirements. In many instances, product and process engineering have been performed simultaneously and interactively, supported by high-performance computing environments and advanced technologies in the areas of materials, process development, simulation, and ultra-precision production. The technology assets and expertise available within the DOE facilities thus provide a strong foundation for the TEAM program.

The TEAM philosophy stresses cooperation with other agencies, universities, and industry-sponsored programs to promote a more agile, cost-effective, and capable national industrial base. The U.S. Department of Defense (DoD), National Institute of Standards and Technology (NIST), National Science Foundation (NSF), and other agencies have a wealth of experience and ongoing programs with which TEAM is coordinating its activities. Industry offers tremendous capabilities to advance manufacturing technologies, but costs and competitive pressures present barriers to their full exploitation. TEAM, therefore, focuses on advancing pre-competitive technologies from which all types of industries can benefit through shared investment.
The TEAM partners recognize that a strong manufacturing infrastructure is essential in integrating advanced manufacturing technologies to enable quantum improvements in manufacturing efficiency, product quality, responsiveness to customer needs, life-cycle cost, and time-to-market. The TEAM program is therefore focused on providing key technologies and tools that support this infrastructure through adherence to standards and the concepts of interoperable, “plug-and-play” systems. This focus ensures that the technologies delivered by TEAM will have maximum value to both commercial and defense manufacturing operations.

TEAM’s process of identifying critical needs and defining current technology development efforts in the private and federal sectors to identify gaps that TEAM can fill began in September 1992 with an industry workshop to gauge potential interest. In follow-on workshops and working meetings, industry and government participants collaborate to plan and revise the TEAM program. Participating organizations include:

- A diverse group of American firms and consortia representing many industrial sectors, encompassing aerospace/defense, automotive, machine tools, robotics, consumer electronics, and software.
- Federal facilities and agencies including Lawrence Livermore National Laboratory, Los Alamos National Laboratory, the Oak Ridge Centers for Manufacturing Technology, the Oak Ridge National Laboratory, the AlliedSignal Kansas City Plant, Sandia National Laboratories, DoD, NIST, and NSF.

2 TEAM OBJECTIVES

Capitalizing on the strengths of participating organizations, TEAM is developing and deploying enabling technologies that are the basic building blocks of agile enterprises in any manufacturing sector. Cross-cutting, pre-competitive technologies are being developed and demonstrated in selected, high-priority product vehicle areas to prove their value and reduce the risk associated with full-scale implementation. These technologies are being made available for commercialization. The objectives of the TEAM program include:

- Advance current technologies and develop new solutions that fill technology gaps in the national agile manufacturing agenda.
- Demonstrate and deploy technologies that benefit multiple industrial sectors and meet the critical needs of the defense complex.
- Facilitate commercialization and rapid deployment of technologies to maximize near-term benefits to industry and government.
- Improve the access of small businesses to advanced technologies.
- Integrate, demonstrate, and deploy a comprehensive system of technologies to support agile manufacturing within large, complex, geographically-dispersed virtual enterprises.
Technologies that satisfy these objectives provide specific benefits to TEAM partners while boosting the capabilities, quality, and cost-effectiveness of the nation's industrial base. By working together within TEAM, large and small manufacturers, technology suppliers, academic institutions, and participating federal agencies and consortia leverage each other's expertise and resources to achieve their mutual agile manufacturing goals.

3 TEAM MODELS AND ORGANIZATION

The TEAM Strategic Plan defines a suite of technology Thrust Area tasks and a technical strategy that provides significant near-term and long-term benefits to the commercial and defense manufacturing sectors. The foundation of the program is a vision of agile, virtual enterprises where organizations can swiftly and cost-effectively bring products from design to production and respond dynamically to changes in business environments and product requirements.

While the TEAM program is not intended to address the entire product life cycle, it recognizes that all phases of the life cycle must be considered in the product realization processes of agile enterprises. Therefore, an agile enterprise model, product realization model, and agile toolbox model that assists in evolution of approaches have been developed and continue to be refined to meet the strategic objectives of the program. The characteristics of an agile enterprise and the premises of agility have been defined and tested (in concept) in several major studies. The visions of agility developed by Agile Manufacturing Enterprise Forum and industry are accepted by TEAM as guideposts for the development of agile technologies, and TEAM looks to these entities to lead the evolution of agile enterprise definition. However, the specific scope of work performed within the program continues to be driven by the near-term priorities of TEAM's industry and government partners.

Three models assist TEAM partners in defining the scope and role of the TEAM program within the larger scheme of the agile manufacturing business enterprise. The models also assist in communicating program scope and progress, in guiding strategic and tactical planning, and in documenting deliverables.

3.1 TEAM Enterprise Model

A top-level model of a generic agile manufacturing enterprise is shown in Figure 1. The product realization process starts with customers, who may present themselves in several different forms (e.g., discrete individual customers, groups, or market segments). The ability to quickly respond to customer inquiries with accurate and detailed information about cost, performance, and schedule is vital. These activities are captured in the first portion of the model, where the voice of the customer drives enterprise responses and partnering decisions through use of agile business practices to translate customer needs and desires into product design and manufacturing requirements.
The TEAM Enterprise Model portrays a generic manufacturing business enterprise and identifies the enterprise functions addressed by the TEAM program.

The second and third sections of Figure 1 contain the major focal points of TEAM. The agile product realization concept operates on the premise that once customer needs are established to the point that product requirements can be discretely defined, the producibility, process modeling, simulation, analysis, and resource planning functions interoperate seamlessly and concurrently to provide accurate assessments of cost, performance, and schedule for conceptual product realization approaches. These capabilities enable the enterprise and the customer to rapidly evaluate tradeoffs of key factors so that an optimized, validated design may be determined for the product and its design and manufacturing execution processes.

With the defined product design and product realization strategy, the information that drives the manufacturing operations must be compiled to create an initial product realization script and delivered to the right functional elements at the right times to support execution. Simulation and optimization tools take the script to the next level of detail to fine-tune the best methods, materials, and processes for manufacturing execution. Once this concurrent product, process, and resource optimization is complete, the manufacturing script is prepared. The manufacturing script is the total package of information required to produce the product accurately, efficiently, on time, and within budget, parsed and parceled so every function in the manufacturing process has what it needs, when it needs it.
In the execution step, intelligent closed-loop manufacturing processes are performed with 100% assurance of a quality result. Such surety is possible because control models have been developed for each process, and the parameters of each model are supplied in the manufacturing realization script for every product. The process control models are the result of a systematic process called deterministic manufacturing, wherein processes are characterized by defining all of their parameters, quantifying their interactions and impacts on process performance, defining cost and performance tradeoffs to define control limits, and developing monitoring and control strategies that ensure compliant execution.

The latter portions of the enterprise model portray the distribution, support, and environmental responsibilities of the product life cycle and illustrate the necessity for knowledge about all aspects of the product life cycle to flow throughout the enterprise. Support for products must be more responsive and easier to access than is currently the norm, particularly for defense systems. On-board diagnostics, interactive electronic linking to repair centers, and modular design for repair and upgrade are a few mechanisms that can enable and support realization of “lifetime” contracts with loyal, satisfied customers.

Finally, the agile manufacturing enterprise must embrace complete concept-to-retirement responsibility for its products. Environmentally benign materials can be preferentially selected in the product design process, and products can be configured from inception for isolation of materials for recovery and reuse. Exchange of parts having age- and use-related failure modes, and remanufacture of components remaining after product retirement, each have advantages in a cost-conscious and environmentally responsible world.

3.2 TEAM Product Realization Model

The TEAM product realization process (see Figure 2) is driven by needs input from customers and supplier stakeholders to provide solutions in the form of products and services. This process is based on development and execution of a product realization script managed in a concurrent environment. The script is optimized for performance and value by trading off critical parameters in the product, process, and resource domains during the composition phase, where stakeholders access and influence the development of the script. The script is realized during the execution phase, where acquisition, allocation, fabrication, and assembly are conducted to produce deliverable products.

The script is based on enterprise knowledge captured from past experiences and includes data, information, and domain knowledge for products, product models, manufacturing processes, and enterprise resources. These knowledge bases are integrated through an open-architecture infrastructure that enables team collaboration, interoperability, and portability of tools. Relevant terms are defined below:

- **Baseline Script** – A low-fidelity version of the product realization script.
- **Domain Knowledge** – The fusion of data and information about experience in product, process, and resource environments.
- **Manufacturing Script** – The subset of the product realization script necessary for manufacturing of product.
- **Product Realization Script** – The integrated collection of the following elements including, but not limited to, (1) requirements definition, (2) design and analysis data, (3) product, process, and resource data and models, and (4) verification information necessary to make (realize) products.
- **Product Realization** – The process for transforming needs into solutions in the form of products and services.

![Figure 2](image)

**Figure 2**  The TEAM Product Realization Model describes the steps of the product life cycle addressed by the TEAM program.

**Concept Optimization**

Concept optimization captures customer requirements and translates them into optimized concepts in the form of a baseline script necessary to initialize the design optimization process. This is accomplished through an iterative process of capturing and prioritizing customer needs, synthesizing solutions to those needs, establishing target parameters for these solutions, analyzing and optimizing these parameters relative to design targets, and creating the baseline script. This process is managed by a customer-supplier team using knowledge-based requirements management tools in a concurrent environment supported by an interoperable product realization infrastructure.
Concept optimization maximizes the team’s ability to innovate and influence product, process, and resource concepts prior to detailed design. Because this optimization is at a parametric level, a rough-order-of-magnitude estimation of product cost, flow time, and functional performance can be made prior to design. This enables the team to balance customer needs with enterprise capabilities prior to commitment of resources. Conflicts between internal and external expectations and capabilities can thus be resolved early in the product life cycle.

**Design Optimization**
Design optimization translates low-fidelity baseline scripts into high-fidelity product realization scripts. The design optimization process concurrently manages three iterative design optimization environments – products, manufacturing processes, and enterprise resources. Each of the design optimization environments is initialized by the baseline script to translate optimized concepts into high-fidelity model-based designs for product realization. Each design environment is based on a design, analyze, and optimize methodology that yields a portion of the product realization script.

The design function employs computer-aided design technology to establish and manage parameters, tolerances, and design margins. The analysis function employs computer-aided engineering tools to model and simulate systems to analyze and validate performance. The optimization function employs computer-aided engineering tools that facilitate experimentation for various design and process configurations.

All process elements are baselined from enterprise knowledge and collaborate, interact, and influence each other through an intelligent infrastructure. Requirements management tools are used to establish customer-driven design targets, and scoring technology is used to validate designs against the targets. This allows the product realization team to iteratively design and validate the optimized product design and the product realization approach against the customer design targets and the enterprise’s capabilities and resources.

**Execution**
The Execution Phase transforms the product realization script into tangible products. Necessary information is extracted from the product realization script to form the manufacturing script, which initializes acquisition, process control, and shop floor control functions. These functions are knowledge-based, enabling translation of the manufacturing script into control and material elements that support fabrication and assembly. The shop floor control function is based on computer-aided manufacturing technology; the fabrication and assembly functions are based on intelligent closed-loop control technology.

Material acquisition, process control, and shop floor control functions are managed concurrently through an integrated infrastructure by enterprise stakeholders to transform the manufacturing script into tangible products and services. Baseline control, acquisition, and production management elements are formulated from enterprise knowledge. The script is deeply rooted in the needs of customers and shop floor stakeholders so that generation of waste is balanced with customer and enterprise needs. Factory capability is considered in
design so that manufacturing process capability and capacity can be managed within expectations of the design. As the product realization script begins to mature, future requirements can be anticipated by the shop floor. Design information can be rapidly transferred to the shop floor. Priorities based on design intent can be leveraged in shop floor decisions. These capabilities all have the effect of minimizing nonconformance, cost, and flow time in the execution of the manufacturing script.

Figure 3  The TEAM Agile Technology Toolbox describes the tools and techniques that support an agile product realization processes.

3.3 TEAM Agile Technology Toolbox Model

One of the TEAM program goals is to populate a “toolbox” of modular manufacturing technologies that support operation of integrated agile manufacturing enterprises (see Figure 3). These technologies are being jointly developed, integrated, and refined by technology developers, industrial users, government agencies, national labs, and universities. TEAM technology development is focused on the five cross-cutting Thrust Areas that span the manufacturing product realization process. The TEAM Thrust Areas are discussed below:
• **Product Design and Enterprise Concurrency** – Integrated product design tool suites that interface directly with virtual manufacturing and manufacturing planning and control systems to reduce cost and time in design processes while enhancing quality and agility.

• **Virtual Manufacturing** – Advanced modeling and simulation capabilities in the areas of product performance, material removal, turning, forming, and enterprise modeling to optimize both product and process designs for cost-effectiveness and quality.

• **Manufacturing Planning and Control** – Integrated manufacturing planning and control systems including macro and micro planners and an agile shop floor control system to optimize the design and execution of manufacturing operations for best use of resources, materials, supplies, and manpower.

• **Intelligent Closed-Loop Processing** – Advanced, intelligent closed-loop processing capabilities including validation of open-architecture controller capabilities for high-value manufacturing processes.

• **Enterprise Integration** – Manufacturing and business systems integration tools that support formation and operation of virtual enterprises (business entities with multiple partners operating as an integrated unit regardless of geographic separation).

4 TEAM ENTERPRISE INTEGRATION

The Enterprise Integration Thrust Area of TEAM is providing a framework for interactive communication of digital product and process definitions in a distributed, heterogeneous, interoperable environment. The goal of this Thrust Area is to create a robust architecture and a suite of tools for seamless integration of all manufacturing enterprise operations, enabling manufacturers to maximize the benefits of advances in agile manufacturing. This Thrust Area in conjunction with several other organizations is developing the integration architecture needed to ensure that manufacturing data may be communicated seamlessly, accurately, and securely within the virtual enterprise to support optimized manufacturing processes.

4.1 Communications Network

Establishment of an electronic communications network is the first step in creating the virtual enterprise of TEAM information repositories accessible to all partners. This network, initially established in 1995, uses the Internet for a backbone, and provides for: (1) an effective communication mechanism among TEAM participants; (2) an interactive, collaborative desktop environment for virtual collocation of TEAM members; (3) an infrastructure that supports enterprise concurrency; and (4) the agility to incorporate new technologies as needed.

All TEAM information is maintained on servers accessible from the Internet. Worldwide Web technology is used to distribute TEAM information and make on-line training and education assets available to all participants. The same tools and techniques deployed by
TEAM for use over the Internet can be used over an individual company’s “Intranet” with little or no reconfiguration.

4.2 Technical Architecture Specification

Standardized interfaces, data structures, object services, and intelligent agents are technology enablers for flexibility in the access, delivery, exchange, and sharing of information within any agile enterprise. TEAM is addressing these needs through development of a Technical Architecture Specification (TAS) – an organized collection of information technology guidelines, standards, and preferred deployment strategies that serve as a guideline for technology development and implementation. For TEAM, or any agile enterprise, the TAS provides a central reference and architectural guidance for plans and decisions that affect an enterprise’s information technology infrastructure. The TAS is maintained as a living, World Wide Web-accessible document.

4.3 Distributed Object STEP Repository

Collaboration based on shared data with common identification is an agile enterprise requirement. The infrastructure developed by TEAM must be able to adapt to changing customer demands, and a standards-based approach ensures this requirement is satisfied. Enterprise Integration promotes the evolution from an infrastructure that supports CALS-based exchange via electronic files to STEP-based information sharing via a distributed object environment. TEAM is moving as rapidly as practicable toward a distributed object environment so that all TEAM participants can reap the object-oriented programming benefits of encapsulation, inheritance, reuse, and polymorphism.

5 CONCLUSION

As the TEAM program completes its second year of effort, the TEAM partners are beginning to realize the program goals with the delivery of initial results from the Material Removal Product Vehicle demonstration and a strong start on populating the TEAM toolbox of agile manufacturing tools. This review of the TEAM program reflects the progress made to date as well as the refinement of program vision and operating principles implemented in response to feedback from many of TEAM participants and partners. With the direct support of more than forty participating organizations and the development of “leveraging” relationships with numerous other programs and organizations with interests in the advanced manufacturing arena, the TEAM program continues to pursue its goals.
6 REFERENCES


7 ACKNOWLEDGMENTS

The authors of this paper would like to express their appreciation to all of those dedicated individuals who have participated in the TEAM program. We would like to especially thank Diane Bird, Bob Burleson, Mark Bruns, Buddy Hewgley, Howard McCue, Bob Meier, and Mike Murphy.

8 BIOGRAPHY

W. Harvey Gray (Ph.D. Mechanical Engineering, Vanderbilt University) is the Director of the Computational Center for Industrial Innovation (CCII) at the Oak Ridge National Laboratory (ORNL). He has held a variety of positions at ORNL since joining the staff in 1974. His current position in the Center for Computational Sciences involves managing the CCII user facility which serves as the focal point for industrial partnerships with ORNL in the challenging area of high-performance computing. The CCII is a U.S. DOE National User Facility (http://www.ccs.ornl.gov/ccii). Previously, he was the Enterprise Integration Thrust Area Leader for the TEAM program.

Richard E. Neal (M.S. Electrical Engineering, University of Tennessee) is the program manager of TEAM and is a co-principal investigator of the Next Generation Manufacturing project. He is a licensed professional engineer at the Oak Ridge Centers for Manufacturing Technology. During his 25 year career, he has held positions in manufacturing systems development and program management. Previously, he developed hardware and software systems for the intelligent control of the manufacturing processes associated with novel coating applications. Also, he led the Integrated Manufacturing Information and Control System project which was an early application of knowledge-based systems in an automated manufacturing environment.

C. Kim Cobb (M.S. Computer Science, University of Tennessee) is a Computing Specialist in the Data Systems Research and Development Division at the Oak Ridge Y-12 Plant, a DOE facility managed by Lockheed Martin Energy Systems (LMES). He is the Enterprise Integration Thrust Area Leader for the TEAM program. Prior to joining the TEAM program, he designed and implemented a plant-wide electronic document management system, he led a project to electronically capture and index employee medical records, and he represented LMES during an analysis and design of an electronic document management system for the International Thermonuclear Experimental Reactor.