Munitions Manufacturing: A Call for Modernization

Committee to Evaluate the Totally Integrated Munitions Enterprise (TIME) Program, National Research Council

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Munitions Manufacturing

A Call for Modernization

Committee to Evaluate the Totally Integrated Munitions Enterprise (TIME) Program
Board on Manufacturing and Engineering Design
Division on Engineering and Physical Sciences
National Research Council

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Preface

The U.S. Army has, as one of its responsibilities, the role of single manager for conventional munitions for all of the armed services. In this role it is responsible for ensuring that an adequate manufacturing capability is maintained within the munitions industrial base (MIB)—the total collection of munitions manufacturing facilities in both the private and public sectors—to meet the combined services' munitions requirements. The Department of Defense's (DoD's) current replenishment policy stipulates that the munitions stockpile must be able to meet peacetime needs (training, testing, replacement of obsolete weapons, sales to foreign governments, and weapons upgrading) and support two near-simultaneous major regional conflicts. It further stipulates that sufficient manufacturing capability be retained to replenish the stockpile within 3 years following such conflicts (GAO 1996a). Under this policy, there is no longer a requirement to surge the MIB (rapidly increase production) during conflicts. However, production rates are to be increased following conflicts until the stockpile has been replenished to its specified level.

The Army has a twofold plan to achieve rapid replenishment by (1) increasing production at dedicated munitions manufacturing facilities, and (2) subcontracting to qualified commercial facilities that agree to maintain dual-use manufacturing capabilities. The Army's ability to utilize commercial firms for rapid replenishment by means of technology and process transfer, however, is severely hampered by the relatively primitive state of government-owned munitions facilities, which generally are not equipped to make effective use of information systems and modern manufacturing technologies.

Similarly, the Army's ability to introduce new munitions within a reasonable time frame is unacceptable by modern industrial standards. Its munitions development and manufacturing enterprise lags far behind that of most commercial organizations in the use of commercially available information technologies, such as computer-aided design and computer-aided manufacturing systems, communications networks, commercially available process controllers, and Internet-based communications. Consequently, design and development cycles are far too long, and transferring a new munition into full-scale production is a lengthy, inefficient, and costly process of trial and error. The lack of state-of-the-market information systems inhibits effective communication within the supply chain. The Army has yet to take advantage of the information and communications technologies mentioned above for creating direct, real-time links between manufacturing and business (or enterprise) processes such as financial and management reporting and production control systems.

The Totally Integrated Munitions Enterprise (TIME) program was initiated in 1997 with the objective of updating the Army's munitions manufacturing capability. The program was to focus on reducing the time required for the development of new munitions and their transition to production. It was also to focus on creating the ability to communicate electronically among various elements of the MIB in order to more rapidly and cost-effectively replenish stockpiles following conflicts. One of the goals of the program was to achieve an integrated solution that tied together all elements of the business enterprise from the Department of the Army down to the shop floor, including product design and testing, the supply chain, production, logistics, production scheduling and control, financial accounting, performance measurement, and overall management reporting.

The TIME program is being managed by the Armaments Research, Development, and Engineering Center (ARDEC) of the Tank-Automotive and Armaments Command (TACOM) at Picatinny Arsenal in New Jersey. ARDEC's mission, which may be found online at <http://w3.pica.army.mil/ardec/>, is as follows:

> …to provide research, product development and full life cycle engineering for ammunition, weapons, sophisticated fire control (targeting) technology, and explosives and propellants. We serve our customers by exploring advanced technologies, designing new products, supporting the manufacturers with product and manufacturing know-how, trouble shooting user problems in the field and supporting demilitarization (demolition).

TACOM-ARDEC requested that the National Research Council (NRC) evaluate the TIME program and make recommendations for future direction. In response to that request, the NRC established the Committee to Evaluate the TIME program under the direction of the Board on Manufacturing and Engineering Design. The statement of task is included in the Executive Summary and in Chapter 1. The committee based its findings on detailed presentations by participants in the TIME program, site visits, a review of selected literature, and, perhaps most important, a diverse base of experience in industry and academia.

Chapter 1 of this report provides background information on the U.S. munitions industrial base and on DoD's changing policies and requirements and describes the TIME program. Chapter 2 assesses TIME'S approach to enterprise integration (enterprise architecture, networking, and systems); Chapter 3 assesses the program in terms of its impact on routine munitions production and replenishment. TIME'S approach to product realization, with an emphasis on the introduction of new products, is covered in Chapter 4. Chapter 5 looks at machine tool controllers, particularly TIME'S heavy investment in the Open Modular Architecture Controller. Chapter 6 describes the various demonstrations that TIME includes for validation purposes, and Chapter 7 benchmarks the TIME program against two previous NRC studies dealing with manufacturing: *Visionary Manufacturing Challenges for 2020* (NRC 1998) and *Defense Manufacturing in 2010 and Beyond* (NRC 1999). In Chapter 8 the committee presents its overall conclusions and recommendations. Appendixes A, B, and C describe some related efforts, Appendix D consists of short biographical sketches of the committee's members, and Appendixes E and F contain a glossary and an acronyms list, respectively.

Joe H.Mize, *Chair*
Committee to Evaluate the TIME Program

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This report has been reviewed by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the authors and the NRC in making the published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The contents of the review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to the thank the following individuals for their participation in the review of this report: Henry Alberts, University of Maryland; Richard Curless, Cincinnati Machine; George J.Hess, Ingersoll Milling Machine Company (retired); Richard H.Johnson, consultant, Alexandria, Virginia; Kenneth J.Laskey, SAIC; Thomas Munns, ARINC; Hyla Napadensky, Napadensky Energetics, Inc. (retired); and John Stenbit, TRW, Inc.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations and they did not they see the final draft of the report before its release. The review of this report was overseen by James J.Solberg, Purdue University. Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Finally, the committee gratefully acknowledges the support of the staff of the Board on Manufacturing and Engineering Design, including Bonnie Scarborough, study director (until November 1999); John F.Rasmussen, study director (until September 2000); Patrick J.Doyle, study director (since September 2000); Teri Thorowgood, research associate; and Judith L.Estep, senior project assistant.

Contents

Executive Summary

The current state of U.S. munitions manufacturing presents some complex challenges. The United States has huge stockpiles of certain conventional munitions. Some are becoming obsolete and others are becoming unusable owing to age. There is overcapacity for manufacturing most conventional munitions, even though many of the production processes are inefficient, costly to operate, and obsolete by commercial standards. The introduction of a new munition typically requires 10 to 15 years, far longer than comparable product introductions in commercial facilities.

The usage rate of conventional munitions has dropped dramatically since the end of the Cold War, as a result of (1) reductions in the size of our armed forces; (2) significant reductions in the defense budget, particularly in munitions procurement; and (3) the introduction of precision-guided munitions. The technology used in munitions is changing rapidly, unlike the technology deployed in producing them. Munitions manufacturers are hard pressed to design, test, manufacture, deploy, and maintain new munitions in a timely, cost-effective manner. The product life cycles are shorter, so production quantities are smaller and the per-unit costs are higher, all at a time when tremendous pressures exist to decrease costs, increase quality, and deliver more rapidly. In addition, the munitions industry has undergone significant consolidation, marked by many plant closings and mergers. The skilled workforce has been reduced substantially through a combination of layoffs and retirements.

There is disagreement at the highest levels of the U.S. defense establishment regarding the nature of future potential military engagements and the role of conventional munitions in those engagements. One view foresees most future military engagements as consisting of surgical strikes with precision weapons. The opposing view is that many future military engagements will involve large ground forces involved in hand-to-hand combat using conventional (although ever-improving) weapons and munitions. The committee does not have the expertise to make a final determination on this issue. However, it believes that neither of these extreme views is likely to be correct far into the future. Until this issue is resolved, the United States should progress under the assumption that, to be prepared for the range of potential conflicts, improvements in both precision-guided and conventional munitions will be required.

Against this backdrop of conflicting views and pressures, the Army is attempting to ensure that the munitions industrial base (MIB) can fulfill its mission. One of the initiatives being undertaken is the Totally Integrated Munitions Enterprise (TIME) program, the subject of this report.

TIME assumes that munitions production during peacetime will be conducted primarily in “organic” facilities—that is, in government-owned/government-operated (GOGO) and government-owned/contractor-operated (GOCO) dedicated munitions factories. Current Department of Defense (DoD) policy is to maintain a munitions stockpile sufficient to supply U.S. and allied forces engaged in two near-simultaneous major regional conflicts. Following conflicts, the munitions stockpile is to be replenished by (1) increasing production at dedicated organic munitions factories, and (2) subcontracting the remaining required production to qualified commercial firms by means of contracts that allow their facilities to be converted from civilian work to munitions manufacturing.

A key assumption of the TIME program is that rapid replenishment can be accomplished by transferring technology and processes to commercial firms via electronic communications networks. Thus, it is envisioned that a virtual munitions enterprise can be rapidly formed and activated using advanced information and communications technologies.

STATEMENT OF TASK

The Army asked the National Research Council (NRC) to evaluate the TIME program and make recommendations for future directions. Specifically, the committee was asked to (1) review the goals, objectives, and activities that currently constitute the TIME program, including those related to manufacturing process controls, the integration of operations and business processes, and site-to-site communications; (2) develop a coherent description of the elements and activities of the TIME program and the manner in which they interact; (3) benchmark the TIME program against pertinent state-of-the-art best practices for enterprise architecture and functions such as enterprise management, supply chain management, communications, production design and development, process and machine controls, and shop floor controls; (4) evaluate the extent to which these activities address the manufacturing recommendations and challenges identified in two recent NRC reports, *Visionary Manufacturing Challenges for 2020* (NRC 1998) and *Defense Manufacturing in 2010 and Beyond* (NRC 1999); (5) identify needs for further development and recommend adjustments to the TIME program, including policy changes, to enable the program to successfully address the challenges of munitions development and manufacturing; and (6) identify potential applications for TIME approaches and technologies within the Army, the DoD, and commercial facilities.

MAIN FINDINGS

This and previous studies, including those from the National Defense University (NDU) (NDU, 1996, 1997, 1998), have identified a number of major problems in the GOGO and GOCO MIB in the United States:

- Widespread obsolescence of manufacturing equipment and processes;
- Weak quality control of processes;
- Scarcity of machine tool numerical controllers;
- Outdated, inefficient, and costly product realization processes (sequential versus concurrent);
- Failure to use information and communications technologies;
- Minimal use of computer-aided design (CAD), computer-aided manufacturing (CAM), and computer-aided engineering (CAE), including modeling and simulation;
- Paucity of up-to-date skills and knowledge on the part of the workforce;
- Lack of a modern supply chain management concept for the munitions enterprise;
- Absence of life-cycle cost considerations; and
- Failure to explicitly address environmental concerns.

These problems have developed over a long period of time. Their seriousness is now becoming apparent as the Army struggles to deal with the new realities described earlier.

The committee's major findings relative to the TIME program are as follows:

- TIME was created as the result of a congressionally directed initiative, or plus-up, rather than through the DoD/Army budget. Thus, ownership, accountability, and funding for the program have been outside the normal DoD/Army/Manufacturing Technology program (ManTech) chain of command.
- While this funding indicates the interest of Congress in munitions modernization and much of the TIME program addresses critical problems, the program appears to have been driven too much by contractor interests and desires and too little by the need to solve the most critical problems of the MIB.
- Based on the information provided to the committee, no financial justification was done on either the overall TIME program or the individual subprojects. Such analysis is the main tool used by private industry to prioritize development projects.
- The funding for TIME can support only limited technology demonstrations. Considerably greater funding will be required to accomplish a broad-based modernization program.
- The TIME program suffers because it was apparently not the result of a strategic planning process as practiced in commercial facilities. The absence of formally stated mission, goals, objectives, and metrics made it difficult to see the total program in context and to assess its progress.

- A disproportionate amount of TIME funds and effort (see Table 1–2) has been directed at development of the Open Modular Architecture Controller (OMAC). Substantial additional investment remains before the OMAC will have sufficient capability to return any of the investment in it. Although some of its potential capabilities may someday benefit the munitions industry, no compelling needs or substantial returns on further investment were presented to the committee.
- The Army's organic (GOGO and GOCO) munitions manufacturing enterprise is plagued by fundamental machinery and process problems that must be addressed in the near term. Substantial modernization is needed if the nation's war fighting requirements are to be met.
- The government-run facilities have almost no CAD/CAM capability, the lack of which calls into serious question the Army's ability to transfer technology and processes to commercial dual-use facilities for stockpile replenishment. This technology transfer is the key tenet of the TIME program. Much of the design and process data for conventional munitions exists on paper drawings or is not documented at all. Some of these data have been scanned into electronic databases, but in most organic facilities the capability to access and use these databases is limited or nonexistent. Given the relatively neglected state of its organic munitions manufacturing enterprise, the Army would benefit substantially from the rapid implementation of stand-alone, commercial off-the-shelf (COTS) CAD/CAM systems, appropriate databases, and adequate communications networks.
- The Army has yet to begin to take advantage of techniques such as information-based supply chain management that are used in commercial industry to reduce obsolete inventories and increase the responsiveness of original equipment manufacturers and suppliers to changing customer needs.
- The TIME program is attempting a very large enterprise integration effort. It is the committee's opinion, based on its experience with similar endeavors, that significant increases in funding would be required to meet the objectives of the program.
- Modernizing the munitions industry presents a complex problem that includes a combination of management, political, economic, and cultural, or people, issues, not just technical issues. Yet the TIME program was set up to focus almost exclusively on the technical aspects of the problem.

MAIN CONCLUSIONS

Specific conclusions are embedded in the chapters of this report. The main conclusions pertinent to the committee's charge are collected here and presented in aggregate form.

- The problems that the TIME program addresses are very real and very urgent. The U.S. MIB is largely obsolete, expensive to operate, inflexible, and slow in its responsiveness to changing requirements.
- Many of the fundamental elements required to support the DoD munitions replenishment policy are not adequate or not in place. Thus, the committee is concerned about the Army's ability to support two near-simultaneous regional conflicts with the needed quantity of conventional and advanced munitions. This concern has been expressed in other studies that dealt with this issue (NDU, 1996, 1997, 1998).
- The DoD/Army have not followed the accepted commercial business practice of investing continuously to keep their munitions manufacturing infrastructure (facilities, equipment, and workforce) reasonably up-to-date.
- The method of funding TIME—namely, through a direct congressional appropriation—has meant that DoD is not involved in planning and managing the program.
- The committee perceives that DoD and the Army command have neither assumed ownership of the TIME program, nor demonstrated budgeting commitment to it.
- The TIME concept does not appear to have been well communicated within the Army, and the committee is concerned that the Army has not accepted TIME as part of its munitions enterprise.
- TIME needs strong support from DoD and the Army leadership to be successful.
- The TIME program's objectives are ambitious based on the program's funding history.
- The heavy focus of the TIME program on the OMAC has consumed resources needed for other important dimensions of TIME. The committee is not aware of any munitions manufacturing need (as opposed to hoped-for higher-performance control technologies) that cannot be adequately addressed by today's COTS controllers.
- The TIME program is to be commended for its focus on demonstration projects as a means of trying out complex integrated enterprise systems in a real-life setting and identifying potential problems prior to full implementation and use.
- The integrated munitions enterprise will be especially vulnerable to unanticipated failures because it will consist of a large number of disparate and evolving systems. Because the parts used primarily by dual-use suppliers may rarely be exercised in conjunction with other

parts of the integrated munitions enterprise, a comprehensive program of validation is essential.
- The TIME program is deficient in three important areas: (1) workforce issues, (2) environmental concerns, and (3) life-cycle cost considerations.

The committee believes that the TIME program is developing an approach to an integrated enterprise that may offer potential for other DoD manufacturing enterprises, particularly if the main recommendations of this report are adopted.

MAIN RECOMMENDATIONS

Specific detailed recommendations are embedded in the chapters of this report. Presented here are the committee's main recommendations to managers of the TIME program and to the Department of the Army.

Budgetary and Management Issues

- The TIME program should be reconstituted and built into a DoD/Army initiative to be pursued over the next decade. It should be adequately and consistently funded through the formal DoD and Army chain of command, not through funding that cannot be counted on to continue. As part of its reconstitution, TIME needs to develop a long-term strategic modernization plan that conforms to DoD plans and munitions industry needs and clearly shows ownership, responsibility, and accountability. TIME needs to reset its direction and objectives by taking a bottom-up approach to both new product introduction and replenishment capacity management. It then needs to develop short-term implementation plans with measurable goals and objectives. Furthermore, it should establish

- A clear statement of vision, mission, and goals and communicate this information throughout the Department of the Army, and
- A leadership structure that will clearly identify the responsibility of each organization and participant for the realization of the TIME vision and that will monitor progress toward the program's goals.

- An essential element of the long-term strategic planning effort should be an evaluation of reasonable alternatives for the manufacture of conventional munitions. For example, with the shifting emphasis to precision-guided munitions (PGMs) and the development of the PGMs industrial base, it is possible that that base could also handle the conventional munitions requirements.

- The TIME program should regularly review its goals and objectives, as well as its technology path for achieving those objectives so that it can avail itself of the latest appropriate, well-proven COTS technologies.
- When a long-term strategic plan for TIME has been developed, after the Army has assumed ownership of TIME, and as the TIME program moves toward the implementation phase, substantial additional funding should be made available.
- The committee agrees with DoD's strategy for achieving greater efficiency in munitions procurement by privatizing a substantial portion of the MIB. Accordingly, the committee recommends that the Army transfer production requirements to the private sector wherever possible, limiting the resources needed to upgrade or replace production equipment and systems in GOGO/GOCO facilities that have become obsolete. For those requirements that must remain in the organic base, the Army should upgrade its production equipment and processes to make them compatible with those currently in use by commercial facilities, so that outsourcing for stockpile replenishment becomes a viable option.

Technical and Program Approaches

- The Army should follow the practice of acquiring state-of-the-market, commercially available technologies whenever possible. It should not engage in developing cutting-edge technologies in areas that are not defense-unique.
- The Army should also do as follows:

- Continue the process of benchmarking against commercial industry.
- Continue the process of demonstration projects for the transfer of technological capability.
- Implement CAD/CAM/CAE systems and appropriate employee training.
- Prioritize needs and opportunities in conformance with the architecture and begin to implement the pieces having the highest paybacks, as determined by cost-benefit analyses and strategic military needs.
- Include detailed contingencies for unforeseen disruptions in routine munitions production caused by the introduction of new technologies.
- Develop a human resource plan that parallels the technology plans and enterprise architecture of the TIME program.

- TIME should divest itself of further development of the OMAC and proceed immediately to transfer such work, as is, to commercial developers. TIME should consider the use of OMACs only when they are available as well-proven commercial products and only if they exceed the performance of other commercial controllers.
- TIME should be working diligently to identify and implement the latest commercially proven technologies in conformance with a completed enterprise architecture plan. The essential strategic element in developing and integrating the enterprise architecture is integrated design and manufacturing.
- The Army should contract with commercial process control experts to implement modern COTS control technologies on energetics process equipment in GOGO and GOCO munitions manufacturing facilities.
- The Army should immediately begin to implement COTS CAD/CAM/CAE systems in the munitions industry. The TIME program should investigate and implement COTS packages that enable effective communication between a wide variety of CAD and CAM systems.
- In accordance with the architecture proposed by TIME, the entire acquisition process, from ordering munitions to paying for them, should be automated and integrated into one loosely coupled, unified enterprise system. The TIME program should capitalize on opportunities for cost and inventory reduction that may be available through use of proven commercial industry techniques for integration of supply chains.
- The Army should follow the current industrial practice of developing long-term mutually beneficial relationships with both routine munitions suppliers and its replenishment suppliers. It should also take advantage of changes in government procurement regulations to optimize the performance of its munitions supply chains, especially when needed for replenishment.
- Issues associated with the environmental impact of the production, storage, demilitarization, disposal, and recycling of munitions should play a key role in the TIME program’s long-range plans. TIME should work closely with other DoD programs that are working toward cleaner, greener, armed forces and addressing issues of health and safety.

Special Recommendation

It is strongly recommended that the Army Materiel Command establish a standing peer review committee to provide oversight and guidance to the TIME program. The committee should report to Army managers at a level with both budget development authority for the TIME program and overall responsibility for management of munitions. The committee should conduct an annual review of the TIME program, assess progress, and provide guidance on future directions. The committee should consist of expert representatives from industry, particularly the controls industry, and academia.

1

Munitions Manufacturing in the United States

This chapter describes conventional munitions manufacturing in the United States from a historical perspective and describes the current status of the munitions industrial base (MIB). It also introduces the Totally Integrated Munitions Enterprise (TIME) program and outlines the intent of this study.

HISTORY AND CURRENT STATUS

The MIB can be divided into four categories: (1) conventional munitions, (2) precision-guided munitions (PGMs) (so-called smart weapons), (3) weapons of mass destruction (nuclear, biological, and chemical), and (4) munitions of the future. This study concerned itself primarily with conventional munitions, a category sometimes referred to as ammunition, and only secondarily with smart munitions. The TIME program, however, has the potential to provide a valuable framework for the design, procurement, and fabrication of smart munitions and possibly also for munitions of the future, although weapons in this category are only vaguely defined.

The conventional munitions category includes the munitions fired from (1) pistols, rifles, and machine guns; (2) tanks, artillery, mortars, and ship's guns; and (3) aircraft guns and shipboard air defense weapons.

Conventional munitions also include so-called dumb bombs. These basic, low-technology munitions, often known as "rounds," generally have changed little in their design during the past century. Small arms ammunition typically consists of a metallic (usually brass) cartridge case filled with a propellant charge that is crimped to a projectile, such as a bullet. Rounds typically contain a primer/detonator and/or fuse. The propellant, especially for large rounds, may be stored in separate bags or cases, to be used as needed to achieve the desired range. Except for kinetic energy small arms ammunition, most conventional munitions contain a high explosive, often called the warhead. Electronics are typically nonexistent or a minor part of these munitions.

The current U.S. munitions manufacturing base was originally established to meet World War II (WWII) munitions requirements of the United States and its allies. Selected parts of it were subsequently upgraded to meet the needs of more recent conflicts, including the Korean War and the Vietnam War. The primary emphasis was on the production of massive quantities of unsophisticated munitions. The U.S. munitions supply strategy consisted of maintaining massive stockpiles of conventional munitions while retaining the ability to surge the MIB— that is, to rapidly ramp up production rates—in case of major conflicts. During those years, the United States retained considerably more capacity than it needed, largely because of the massive production capacity established during WWII and also because of fears of a massive land war in Europe.

Entering the 21st century, the MIB consists of two broad categories of facilities, usually called “organic” and “commercial.” The organic category comprises government-owned/government-operated (GOGO) and government-owned/contractor-operated (GOCO) facilities. The commercial base consists of a declining number of commercially owned/commercially operated facilities, consisting of both prime contractors (responsible for end-item production) and numerous subcontractors (suppliers of components to both government and commercial end item munitions producers). As of 1997, the U.S. MIB consisted of three active GOGO facilities, six active GOCO facilities, and fewer than 50 contractor-owned/contractor-operated (COCO) facilities (NDU 1997). These facilities are supplied by numerous (but diminishing) second-and third-tier manufacturers.

During the past several decades there was little incentive to modernize munitions manufacturing equipment and facilities in either the government or commercial sectors, because there was significantly more capacity than needed. Consequently, most munitions manufacturing facilities are at least several decades old and are obsolete even by the most generous standards. Defense planners have relied instead on huge stockpiles of munitions. Although stockpiles enable a rapid response in case of a military crisis, they are expensive to create, maintain, and, in many cases, dispose of when no longer needed. The current government munitions manufacturing base not only is obsolete and, in some cases, in poor condition, but also has extremely high overhead costs (in part owing to low production rates), is inflexible, and is in varying states of readiness for reactivation in case of a national emergency (McWilliams 1999).

While the government-owned MIB has gradually decayed, significant advances have been made in munitions technology. Despite generally low levels of research into concepts for advanced penetrators, energetics, guidance systems, and munitions, new smart munitions, which offer significant advantages to the war fighter, have been developed. The dramatic performance of new PGMs during Operation Desert Storm and the Kosovo conflict demonstrated conclusively that some of these new weapons are far superior to conventional munitions for many applications. Field commanders greatly prefer them and tend to use the newest technology weapons first. This approach, while justified by the goals of rapid victory with minimal casualties, contributes to the massive stockpiles of increasingly obsolete munitions and strongly suggests that future munitions requirements will increasingly focus on new and high-technology smart weapons. Their manufacture requires advanced processing capabilities not found in most of the older munitions factories. According to information presented to the committee by the Army’s Armament Research, Development, and Engineering Center (ARDEC), the United States currently has considerable overcapacity for the production of conventional weapons (McWilliams 1999), but a study by the National Defense University points out that there is an inadequate capacity and capability for advanced munitions (NDU 1996, p. 15–10).

The end of the Cold War has resulted in significant decreases in the DoD budget, especially for weapons procurement. Funds for munitions procurement have declined approximately twice as fast as the overall DoD acquisition budget (NDU 1996, p. 15–6), resulting in lower production, poorer production efficiency, and poorer profitability for the entire MIB. Overhead rates and unit production costs have increased because of uneconomical production rates and because the fixed expenses of idle plant capacity must be covered by the remaining production. In this environment, it is difficult for either the government or commercial firms to justify investments in modernization.

The declining MIB has resulted in a commensurate aging and downsizing of the workforce. Employees have retired or have been released, taking critical skills and knowledge with them. Few new employees have been hired. This loss of critical skills may severely limit the industry's ability to develop new weapons and support future contingencies. The shrinking base has also resulted in a greater percentage of sole-source producers, which in turn leads to reduced flexibility and, in some cases, very little surge capacity.

These driving forces make it difficult for the Army to oversee the manufacture of munitions for all of the armed services. It is responsible for designing, manufacturing, and maintaining munitions that are increasingly sophisticated and difficult to manufacture, while also coming under pressure to achieve higher quality and reliability, shorter acquisition cycle times, and lower unit costs.

The National Defense University issued studies of the munitions industry in 1996, 1997, and 1998 (NDU 1996, 1997, 1998). Considering such factors as the decreasing demand for conventional munitions, the loss of expertise as the workforce is downsized, sharp decreases in munitions procurement budgets, the primitive state of GOGO munitions manufacturing facilities, and the increasing preference of field commanders for smart weapons, these studies reached the following conclusions:

- The current U.S. munitions stockpile, coupled with the production of precision weaponry, appears marginally adequate to meet the DoD requirement of fighting two short (less than 90 days) major regional conflicts. Current trends suggest that in the near future, the MIB might not be capable of sustaining the quality and quantity of munitions required in a prolonged contingency, such as a "short war gone long" (NDU 1997, p. 14–1).
- For PGMs, industry consolidation could pose a threat to continued U.S. technological superiority (NDU 1998, p. 13–1).

THE TOTALLY INTEGRATED MUNITIONS ENTERPRISE PROGRAM

This section examines the history of the TIME initiative; outlines its vision, goals, and objectives; and describes its programmatic activities and current status.

Background

The problems and challenges existing in the munitions industry, as outlined in the preceding section, were elaborated in detail in a study published in 1997 by the Department of Energy's (DoE's) Pacific Northwest National Laboratory (PNNL). This study recommended that the Army "invest and leverage resources among government, academia, and industry to create a flexible industrial base for munitions" (PNNL 1997). In response, a coalition including the Industrial Controls Corporation, Inc., of Shreveport, Louisiana (ICON), DoE's Lawrence Livermore National Laboratory (LLNL), and several industrial firms was formed to address these issues. After a difficult first year, ICON was terminated as a contractor and the initiative was reorganized.

The initiative was called the Totally Integrated Munitions Enterprise, or TIME. Significantly, major funding for TIME came from a congressionally directed initiative, known as a plus-up, rather than from the DoD (either the Army or the DoD Manufacturing Technology program [ManTech]) budget process. Thus, ownership, accountability, and funding for the TIME program have been outside the normal DoD/Army/ManTech chain of command.

DoE, which has stewardship of nuclear weapons, has core competences and technology interests that overlap those of the conventional munitions industry. One of these technology interests involves a perceived need for advanced-functionality, open-architecture controllers, designed such that the architecture may be accessed and customized by engineers at the user organization.

The DoE weapons complex has been active in the development and promotion of such controllers. One avenue for that involvement was through the Technologies Enabling Agile Manufacturing (TEAM) program (described in Neal 2000), which defined requirements for an open-architecture modular controller. In part because of these involvements, Lawrence Livermore National Laboratory assumed a lead role in the management of the TIME program, supported by numerous companies and agencies. Within the Army, the TIME program is overseen by TACOM-ARDEC at Picatinny Arsenal in New Jersey.

Vision, Goals, and Objectives

The high-level vision of TIME is that it will "provide the Department of Defense with a cost-effective, flexible manufacturing capability configured to meet U.S. munitions needs in the 21st century" (Rosenberg et al. undated). This vision of TIME attempts to address munitions manufacturing as a total system, integrating all aspects of the enterprise, including the definition of munitions requirements, the design of products and processes, scale-up, production, the supply chain, logistics, product support, and even the eventual demilitarization of unused munitions.

A major goal of TIME is to support the ability of the Army, as the single manager for conventional ammunition for all of the armed services, to fulfill its responsibilities relative to DoD's current and future munitions manufacturing and replenishment policy. Associated goals include the development of means to greatly reduce product development and deployment cycle times and life-cycle costs and to enable a faster response from dual-use suppliers in times of crisis.

Specific objectives of TIME are as follows (Rosenberg 1999):

- Migration to an environment supporting concurrent engineering and integrated product and process development;
- Support for seamless interaction among all elements of the product realization process by implementing a ubiquitous communication networking capability; and
- Development of the capability to exploit dual-use, nongovernment-owned manufacturing facilities as a means to ramp up munitions production in times of national emergency.

Program Description

This section draws from presentations by Burleson (1999b), Osiecki (1999), Stephens (2000), and Miller (1999). For a detailed task breakdown and schedule of the entire TIME initiative, see ManTech (1999) (excerpted in Appendix A).

The system design concept adopted by the TIME program considers three levels:

- *Level 1: shop floor*. Control of individual and grouped machines and processes within a facility;
- *Level 2: above the shop floor*. Integration of shop floor operations with business processes; and
- *Level 3: external interoperability*. Communication between multiple sites, suppliers, enterprises, and agencies.

Level 1 within a given facility would possess the following capabilities:

- Computer-aided design, engineering, and manufacturing (CAD/CAE/CAM);
- Capture and electronic documentation of manufacturing processes;
- Communication of operations status to remote sites; and
- Rapid transfer of designs and production process technologies to dual-use commercial facilities in the event that replenishment is needed.

Level 2 would consist of the following:

- A distributed communications network;
- General-purpose collaborative tools;
- Quality monitoring systems;
- Management of engineering changes (product design and process);
- A logistics support system;
- A data management and archiving system;
- A manufacturing execution system; and
- Financial, purchasing, personnel, and inventory systems.

Level 3 would embrace the following concepts:

- Replenishment with reduced overhead[1]

- Minimal start-up, tooling, testing, and replenishment times; and
- Scalable and replicable work cells;

- Integration from design to production; and
- Flexibility

- Ability to accommodate small lot sizes to mass production; and
- Affordable, timely production of smart munitions.

Program Elements

The TIME program consists of the following elements, each of which is addressed further in this report (Burleson 1999b; ManTech 1999; Rosenberg et al., undated):

- Enterprise architecture;
- Product realization;
- Networking;
- Open modular architecture control;
- Enterprise systems; and
- Demonstrations.

Metrics for Judging Success

The Army will measure the success of the TIME program using the following metrics (Burleson 1999b):

- Reductions in replenishment base and overhead;
- Reductions in cycle time and acceleration of the acquisition cycle;
- Reductions in life-cycle costs; and

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[1] Originally “without overhead” in prepublication document.

- Success in capturing manufacturing process knowledge and better ability to efficiently transfer it to industry.

Deliverables

The deliverables of the TIME program include the following:

- A framework for integrated product realization;
- A "toolset" of enabling technologies that support the integrated munitions enterprise (Burleson 1999b)

- Product (requirements management, design, and product optimization);
- Process (manufacturability, macro and resource planning, microplanning, and process optimization);
- Analysis (product simulation, process simulation, fixture simulation, workflow simulation, and enterprise modeling);
- Fabrication, assembly, inspection (open architecture controls, work instruction, and manufacturing execution system);
- Integration (Web integration management);
- Enterprise systems (distributed network, general-purpose collaborative tools, quality-monitoring systems, change management, a logistics support system, and a data management and archiving system);

- Implementation of the toolset in a virtual enterprise (Burleson 1999b); and
- Validation of demonstrations of TIME technologies.

Program Funding

Table 1–1 shows the level of effort by fiscal year and program element for each of the participants funded by TIME. An analysis of the "Authorized Funding" column in Table 1–1, after removing funds allocated to "Demonstrations," "Program support," and "Program management," reveals the funding breakdown by project element shown in Table 1–2.

STUDY OBJECTIVES AND APPROACH

Charge to the Committee

After several years of effort on the TIME program and recognizing that the munitions industry is continuing to decay, TACOM-ARDEC requested that the National Research Council (NRC) evaluate the program and offer recommendations that will enable it to better meet the needs of the munitions

TABLE 1–1 TIME Phases I through III: Inclusive Funding, Amount Spent, and Equivalent Headcount

				Equivalent Headcount			
Project Element	Responsible[a] Orgnization	Authorized Funding ($)	Total Spent Through 2/29/00 ($)	LLNL	LCMS	Raytheon	Total
TIME phase I, FY98							
Open modular architecture control	LLNL	3,184,644	2,731,100	7.50			7.50
Program support	LLNL	966,264	1,962,100	1.25			1.25
Total phase I		4,150,908	4,693,200	8.75	0	0	8.75
TIME phase II, FY98							
Architecture	Raytheon	572,212	607,571			2.0	2.0
Product realization	Raytheon	1,111,610	923,608		1.5	3.0	4.5
Networking	LCMS	1,020,288	954,146		3.5		3.5
OMAC extensions	Raytheon	616,470	432,447			2.0	2.0
Demonstrations	LCMS/ Raytheon	2,072,371	1,689,719			3.0	5.0
					2.0		
Program management	LCMS	650,958	423,047				3.0
					3.0		
Total phase II		6,043,909	5,030,538	0.0	10.0	10.0	20.0
TIME phase III, FY99							
Open modular architecture control	LLNL	1,246,580	122,100	7.0			7.0
Product realization	LCMS/ Raytheon	631,457	23,576		2.0	2.0	4.0
Networking	LCMS	410,560	18,800		4.5		4.5
OMAC extensions	Raytheon	357,070	0			2.0	2.0
Enterprise systems	Raytheon	400,236	51,823			3.0	3.0
Demonstrations	LCMS/ Raytheon	1,872,175	15,509		3.0	3.0	6.0
Program support	LLNL	866,867	270,200	1.25			1.25
Program management	LCMS	213,256	958		3.0		3.0
Total phase III		5,998,201	502,966	8.25	12.5	10.0	30.8
Grand total phases I–III		16,193,018	10,226,704				

[a] LLNL, Lawrence Livermore National Laboratory; LCMS, Louisiana Center for Manufacturing Sciences.

Source: T.McWilliams, e-mail communication to the NRC Committee to Evaluate the TIME Program, June 16, 2000.

industry in the 21st century. The Committee to Evaluate the Totally Integrated Munitions Enterprise Program (TIME), formed under the direction of the Board on Manufacturing and Engineering Design, was asked to perform the following tasks:

TABLE 1–2 TIME Funding Breakdown by Project Element

Project Element	% of Total Project Funding	Funding Level ($)
Enterprise architecture	6	572,212
Product realization	18	1,743,067
Networking	15	1,430,847
OMAC	57	5,404,764
Enterprise systems	4	400,236
Total	100	9,551,126

NOTE: Program support, program management, and demonstration costs are not included.

- Review the goals, objectives, and activities that currently constitute the TIME program, including those related to manufacturing process controls, the integration of operations and business processes, and site-to-site communications.
- Develop a coherent description of the elements and activities of the TIME program and the manner in which they interact.
- Benchmark the TIME program against pertinent state-of-the-art best practices for enterprise architecture and functions such as enterprise management, supply chain management, communications, production design and development, process/machine controls, and shop floor controls.
- Evaluate the extent to which these activities address the manufacturing recommendations and challenges identified in two recent NRC reports, *Visionary Manufacturing Challenges for 2020* (NRC 1998) and *Defense Manufacturing in 2010 and Beyond* (NRC 1999).
- Identify needs for further development and recommend adjustments to the TIME program, including policy changes, to enable it to

successfully address the challenges of munitions development and manufacturing.
- Identify potential applications for TIME approaches and technologies within the Army, the Department of Defense, and commercial facilities.

The committee supplemented its expertise and gained a deeper understanding of the issues in several ways. First, several members of the committee visited Picatinny Arsenal to see a first-hand example of the Army‘s munitions facilities and some of the work being done by the TIME program. Second, the committee received an extensive series of briefings on the activities of TIME. The committee also received briefings from defense-related and civilian industries on recently implemented state-of-the-art enterprise integration, supply chain integration, and e-commerce systems.

The committee organized the report into segments that reflect the major thrusts of the TIME program. Chapter 2 discusses the program's approach to integrating the munitions enterprise, including architectures, networking, and systems. Chapter 3 assesses the TIME program's approach to munitions replenishment issues. Chapter 4 delves into the product realization process in the munitions industry. Chapter 5 addresses controllers, which is where the TIME program has spent much of its resources to date. Chapter 6 discusses the important topic of demonstration and validation. In Chapter 7 the committee takes a different look at the TIME program, benchmarking it against the recommendations of two recent visionary NRC manufacturing studies. Finally, Chapter 8 presents several overarching conclusions and recommendations of the committee. Appendixes A, B, and C contain details of other programs that are related to TIME, and Appendixes D, E, and F contain biographical sketches of the committee members, a glossary, and a list of acronyms, respectively.

Frame of Reference for the Committee

The charge to the committee was to assess the appropriateness of the TIME program for modernizing the MIB such that future munitions requirements can be met. For the committee to accomplish its task, an assumption had to be made regarding the future conventional munitions requirements of the combined U.S. armed services. There is considerable disagreement among military experts and strategists as to the nature of future potential military engagements and the role of conventional munitions in those engagements.

At the risk of oversimplification, the two opposing views may be characterized as follows:

- *Surgical strikes with precision weapons*. Those who advocate this view believe that future U.S. military engagements will be similar in nature to Operation Desert Storm and the more recent Kosovo conflict. PGMs were dominant in those engagements. Conventional munitions played a secondary role, particularly in the Kosovo conflict.

- *Hand-to-hand combat*. Other experts believe that the United States would be shortsighted to assume that all future military engagements will be similar to those seen in the 1990s, saying that relegating conventional munitions to history implicitly assumes that the United States will remain the world's only superpower far into the future and will engage in regional conflicts primarily from the air. They conclude that the country must retain a strong capability to support large ground forces with conventional (but steadily improving) weapons and munitions. These experts point to Operation Desert Storm and the Kosovo conflict as evidence that their view is correct. While conceding that precision weapons were extremely valuable in Desert Storm, large ground forces were still required to assure victory. The decision not to use ground forces in Kosovo, they claim, resulted in the deaths of thousands of noncombatants and a situation where long-term deployment of peacekeepers has been necessary.

Those experts subscribing to the latter view are concerned about the condition and deteriorating capability of the conventional MIB. Four recent studies (PNNL 1997; NDU 1996, 1997, 1998) have described the primitive state of the MIB and have questioned its ability to meet the nation's munitions needs in the future. One says, "Trends point to a time in the near future when the U.S. MIB might not be capable of sustaining the quality and quantity of munitions required in a prolonged national emergency such as a short war 'gone long'" (NDU 1997, p. 14–1).

Some of the studies recommend a large investment in modernizing the base. Modernization would include upgrading manufacturing processing equipment (including machine tool controllers); extensive use of CAD/CAM/CAE technologies within an integrated, interoperable environment; and use of modern communications technologies throughout the munitions supply chain. These recommendations envision a dramatic transformation of the currently antiquated munitions factories. Implicit in some of the studies is the assumption that the MIB would produce generally the same array of conventional munitions that is produced today as it also acquires the capability to produce more advanced munitions.

Those experts subscribing to the surgical strike view of future warfare see the world very differently. The demand for conventional munitions has decreased sharply over the past decade, accompanied by sharp reductions in procurement budgets. There has been a major consolidation of commercial firms engaged in munitions production, accompanied by a significant downsizing of the workforce. Precision-guided munitions have become the weapons of choice among military field commanders. Some analysts claim that the emergence of PGMs, along with even more advanced munitions under development, has led to a fundamental shift in U.S. defense strategy: "Since the Vietnam conflict, our shot-to-kill ratios for bombs have shrunk from 1,000 to 1 to just under 3 to 1 at the time of Operation Desert Storm" (NDU 1998, p. 13–5). The shot-to-kill ratio is the number of munitions or shots fired to destroy one target. Also,

> The future of munitions is in high technology applications. Classic ammunition and dumb bombs, the things that go "boom," are no longer the drivers…For the U.S., the MIB is shifting away from conventional munitions to PGMs…. Our reliance on PGMs means we stay strong only while technology drives the development of munitions. The days of massive munitions purchases, go-to-war plans based on overwhelming conventional explosive force, or toe-to-toe ground combat with an equal adversary have passed. Our clear strategic and tactical advantage is in deploying the most technologically sophisticated package of munitions against a less developed foe…. These munitions will not be produced in large numbers and they don't have to be. (NDU 1998, pp. 13–20 and 13–21)

The charge to the committee limited the study scope to conventional munitions. A fundamental question arises when considering the scenarios that indicate a rapidly declining reliance on conventional munitions. The fundamental question is the volume of conventional munitions that will be needed in the future. If the volume is as low as some studies (NDU 1998) assume, there would seem to be little point in modernizing the current MIB for the purpose of providing conventional munitions in large quantities. Under this scenario, the industrial base for PGMs may be capable of supporting production requirements of conventional munitions as well.

Committee Analysis

The committee does not currently have the expertise—if, indeed, anyone has—to determine the nature of future military engagements. However, it concluded that neither extreme view is likely to be correct far into the future. The United States should indeed continue developing and deploying ever-more-capable PGMs. It should also continue developing and deploying ever-more-capable conventional munitions in order to remain prepared for longer term engagements. Until this issue is resolved, the TIME program should progress under the assumption that, to be prepared for the range of potential conflicts, improvements in both precision-guided and conventional munitions will be required.

The committee's vision of the future U.S. MIB can be characterized as follows:

- The MIB must be capable of developing, producing, and deploying a wide array of ever-more-capable munitions, from dumb rounds to advanced PGMs. The distinction between producing conventional and smart munitions should diminish and eventually disappear.

- The MIB must be capable of accommodating new developments in munitions, based on technological breakthroughs, including new explosive and propellant materials, laser-based munitions, and others yet to be conceived.
- The MIB must master the difficult art of manufacturing agility and scalability. It must be capable of responding rapidly to shifting production demands, in terms of both type and quantity of product.
- The MIB must master the difficult art of operating a virtual munitions enterprise, in which win-win partnerships with dual-use commercial manufacturers provide the volume capability to replenish munitions stockpiles.
- MIB production should achieve ever-better product quality, on-time delivery every time, ever-shorter development cycles, and ever-greater life-cycle value.

This vision was adopted by the committee as a frame of reference for evaluating the TIME program.

2

Enterprise Integration

INTRODUCTION

The TIME program is aimed at addressing several munitions manufacturing issues, including determining the proper size of the organic production base; timely realization of affordable, complex smart munitions; and a system for rapid replenishment in national emergencies (Raytheon 2000). It seeks to address these issues through the development and demonstration of a totally integrated munitions enterprise, integrating the design engineering, manufacturing, and support functions over the life cycle of the product. Central to this effort is the development of a flexible, rapidly reconfigurable, distributed manufacturing capability that can function as a single entity on a real-time basis regardless of geographic location.

In response to these challenges, the TIME program has drafted a high-level vision that outlines fundamental concepts for the proposed integrated enterprise (Raytheon 2000). Companion documents outline the network architecture and the controller architecture. A data architecture document will also be created. As envisioned by the TIME program, this integrated enterprise will be capable of the following:

- Rapidly transitioning new products and design changes from design to production in a single iteration;
- Rapidly expanding the operations of the enterprise in times of crisis by integrating geographically separated dual-source contractors with whom the Army will have previously negotiated standby contracts;
- Seamlessly communicating orders, designs, process parameters, and other vital data between facilities having a variety of enterprise resource planning (ERP), supply chain, product design, and communications systems;
- Readily allocating raw materials and production between facilities as needed and monitoring inventory levels and production status in real time; and
- Encouraging interaction between team members and incorporating strategies that will enable optimized design and timely, cost-effective production.

The TIME enterprise architecture is a framework that defines the program vision for the entire enterprise and provides a basis for multiyear planning as TIME continues to evolve.

More important, it provides top-level definition and guidance for the selection and interconnection of hardware and software systems and components, to enable interactivity throughout the munitions enterprise (ManTech 1999). Enterprise architecture activities include the following (Burleson 1999b):

- Developing an understanding of the existing environment;
- Designing the framework for an integrated munitions manufacturing enterprise; and
- Developing a methodology and the initial architecture, including;

- An enterprise framework and development methodologies;
- Identification of enterprise core competencies for integrated product and process development;
- Selection of enterprise enablers; and
- Identification of planning requirements for an agile virtual manufacturing enterprise.

Although current funding levels are sufficient only for technology demonstrations, it is intended that the TIME program will ultimately implement this architecture using, wherever possible, the best demonstrated practices and commercial off-the-shelf (COTS) systems of the private sector. The TIME program anticipates developing enterprise integration technologies only to the extent that they are not commercially available.

Outlining this effort in *Enterprise Architecture* (Raytheon 2000), the TIME program defines enterprise as a unit of economic organization or activity, especially a business unit. It defines architecture as the arrangement of, and interactions among, the components of a system. Thus, enterprise architecture is the arrangement of and interactions among the components of an enterprise, containing the guidelines and rules for the representation of the enterprise framework, systems, organization, resources, products, and processes. This reference architecture has been outlined by the TIME program to serve as an initial benchmark or guide and as a means of assessing the enterprise as it is created and modified over time.

TECHNOLOGIES ENABLING AGILE MANUFACTURING

The TIME program is based, in part, on the results of an earlier program and methodology called Technologies Enabling Agile Manufacturing (TEAM). The TEAM initiative marshaled the forces of many organizations to develop a methodology for integrated manufacturing and to demonstrate that methodology in making sample products at geographically dispersed private and government sites. The TIME program has defined a hierarchical, top-down integration architecture that is designed to mesh with the bottom-up integrated product realization strategy of TEAM.

Background

TEAM[1] was a government/industry partnership developed to create and demonstrate a methodology and a technology toolset for bringing the vision of agile, lean, and responsive manufacturing to reality. TEAM was launched in 1993 and operated until its completion in 1998. During that time, $25 million of government funding was provided. This was more than matched by in-kind contributions from industry.

TEAM was founded on the premise that manufacturing is a product life-cycle system from initial concept definition through design, production, use, and end of life. It was determined that efforts to optimize the efficiency and responsiveness of individual parts of the system must give way to optimization of the entire system, which can, on occasion, have the effect of suboptimizing some of the individual parts. Based on this vision, TEAM produced a strategic plan and a technical plan. It adopted a 3-year, three-phased approach. Because many of the technologies needed for integrated manufacturing already existed in the commercial marketplace, the first target of TEAM's technical group was to find the best commercially available tools for their respective functions and demonstrate those tools in an integrated solution suite. The other targets of the TEAM initiative were interconnected demonstration (limited collaborative environment, partially networked infrastructure, and limited document archiving) and integrated demonstration (collaborative environment, fully networked infrastructure, and structured document archiving).

Methodology

Because terms like "integrated enterprise" and "integrated product realization" were relatively new to some of the program participants, TEAM developed the models shown in Figures 2–1 through 2–3. Figure 2–1 is a simplified view of an integrated enterprise. In an integrated enterprise, all stakeholders are involved in defining and executing the business arrangement. Contracts are established, concepts are evaluated, designs are created, and products are produced, distributed, supported, and retired at the end of their life.

As the focus shifts from design to production of product in an integrated enterprise, the integrated product realization model becomes operative. In this model, concepts are designed and evaluated and a baseline "script" is collaboratively produced by the integrated design team, which includes customers and key suppliers. This script documents all information needed to define the concepts. The design options are evaluated and optimized, in the middle block of the product realization model shown in Figure 2–2, and all information needed to make the product is generated. The manufacturing script becomes the master definition and repository of all of the product information, as well as the processes required to produce and support it. The final block, manufacturing execution, depicts an intelligent environment with closed-loop processing in which all products are manufactured and certified. The entire enterprise operates on a foundation of timely shared and managed

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[1] The description of TEAM in this section is based on information from the TEAM Program Office (Neal 2000).

knowledge. The top-level model in Figure 2–3 depicts the interconnected functions required for integration. Each of the functions necessary to make the product is defined, including the protocols, information requirements, and tools needed to perform the function. The models in Figures 2–1, 2–2, and 2–3 serve as guideposts for integrated product realization.

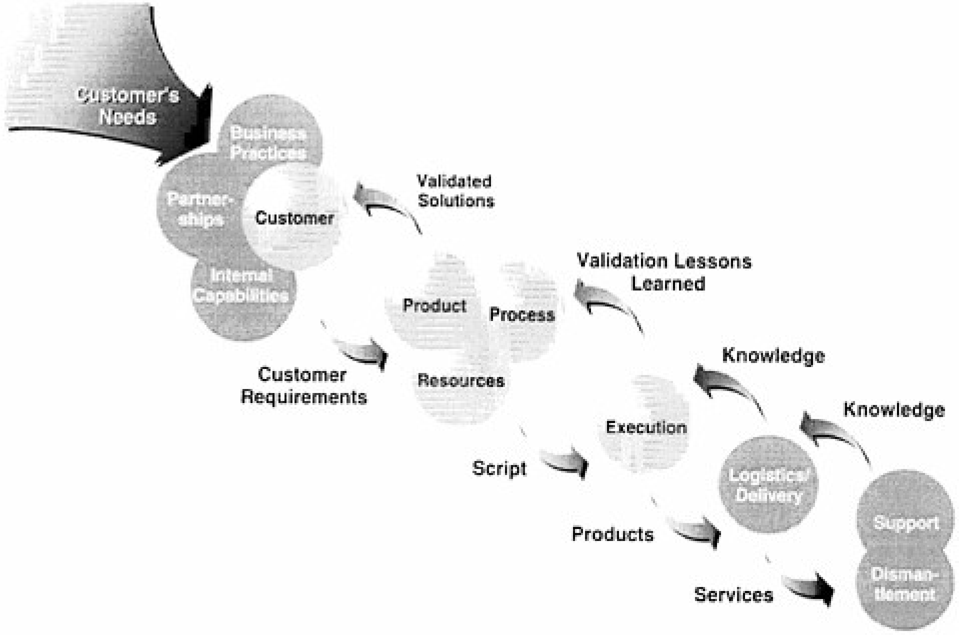

FIGURE 2–1 The integrated enterprise. Source: DoE 1999.

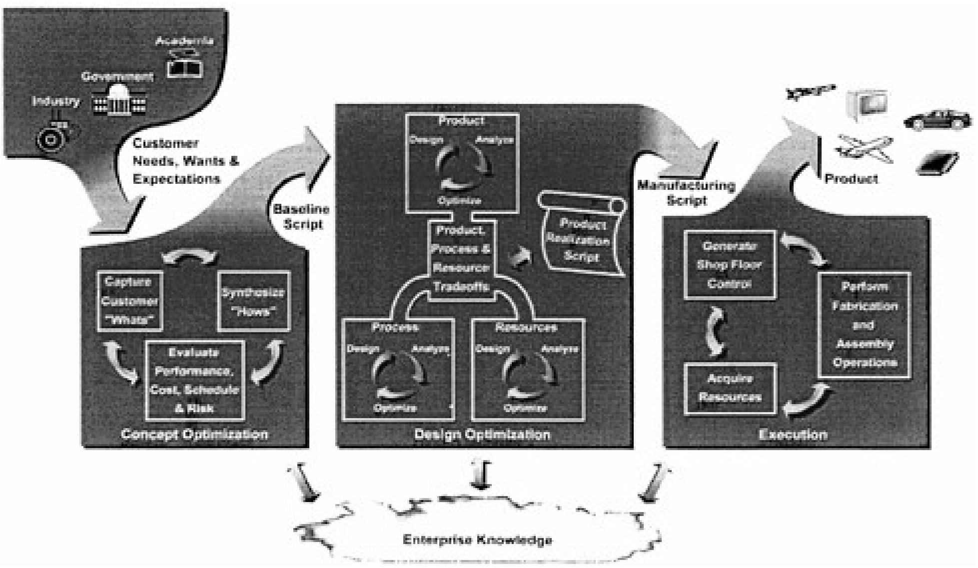

FIGURE 2–2 The TEAM product realization model. Source: DoE 1999.

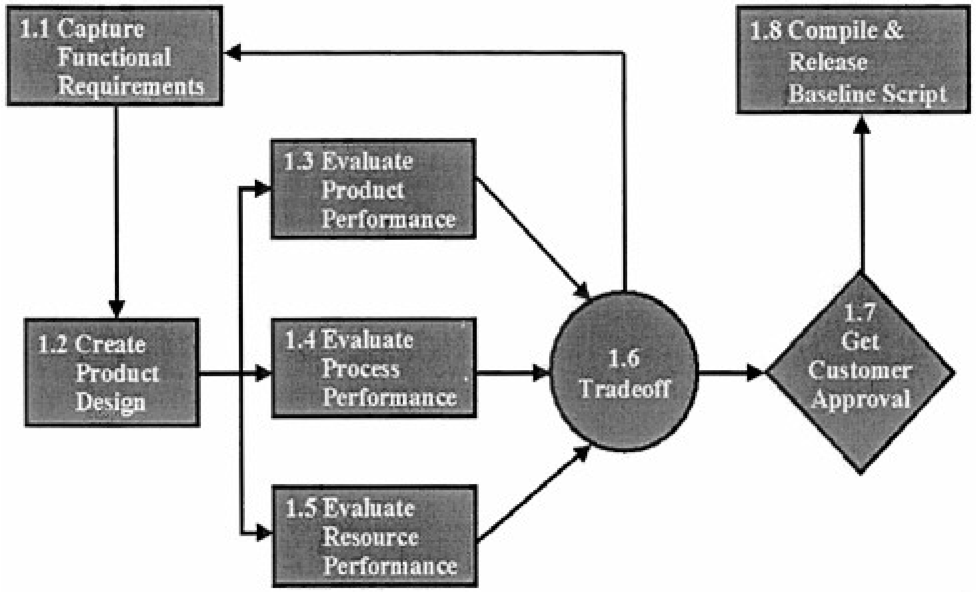

FIGURE 2–3 Workflow model defining functions required for concept optimization. Source: DoE 1999.

After development of models, the next challenge was integration, which proved to be TEAM's greatest hurdle. For most operations, the Internet is an excellent, neutral communications tool. However, an enabling tool was needed to manage the process, and a market search did not identify a COTS product. Therefore, TEAM hired a consultant to produce a framework for the set of Internet access tools, referred to as the Web Integration Manager (WIM). WIM provided multiplatform connectivity and became the product data manager, the repository of all information, the security and configurability control tool, and the workflow manager. In short, it ensured that the project plan could be followed and that every participant in the network had access to information as needed. This Web-enabled approach has the potential to utilize existing databases and legacy hardware and software systems by coding special communication interface "wrappers" and translators. A basic premise of WIM is that any tool that can be connected and can communicate on the WIM can communicate across the enterprise.

Demonstration Projects

After the initial toolset had been defined, the next task was to demonstrate that the tools could be made to operate in a collaborative environment as if they were in the same location (virtually collocated) to produce a sample finished product from design through manufacturing. Although seamless integration was the ultimate goal, expediency necessitated work-arounds for intractable issues such as connection of systems by translators and re-inputting of data, and an interconnected demonstration was designed and conducted for this purpose. A sample prototype machined part was designed and an "enterprise" was established to create it. A network of 11 organizations scattered across the country collaborated in the design of the product, the simulation and refinement of the design, and the creation of the information needed to drive the manufacturing steps. Sample parts were fabricated at General Motors and inspected at Ford. Several universities and small companies observed the demonstration project and produced parts themselves.

The interconnected demonstration validated the methodology of product realization, but it did not address the needs of the integrated enterprise. For the integrated demonstration, an aluminum head for a Corvette engine was selected. The product realization process began with requirements definition, progressed to design and planning, and culminated in production at General Motors. TEAM encountered several significant problems. For example, for the demonstration project to have real-world significance, TEAM had to manage multiple computer-aided design (CAD) systems; launch, integrate, and optimize multiprocess simulations; and drive multiple downstream computer-aided manufacturing (CAM) systems, all from the same product definition files. To address these issues, TEAM adopted an integration architecture called the product realization environment (PRE). Common Object Request Broker Architecture (CORBA) wrappers were developed to "wrap" the tools to interface with PRE. Compatibility between the PRE and the WIM was established to complete the integration. An integrated demonstration, which may be thought of as a virtual cockpit, was developed to enable real-time evaluation of design alternatives through simulation. The simulations addressed both business and technical issues and provided cost and performance information about different options. Approximately 25, mostly COTS, tools were used in the demonstration. At the same time as creation of the Corvette cylinder head, modeling and simulation tools were used for the integrated design of a jet engine exhaust nozzle for Pratt & Whitney.

In the final year of TEAM, each DoE site was charged with using the TEAM tools and methodologies to demonstrate the products for which it was responsible. The demonstrations included a radio frequency system that tested concepts in electronic design and manufacture, a gas transfer system, a metrology master, a tooling set for forming operations, a turned part, and a neutron generator system. Each of the demonstrations used the basic TEAM philosophies but different toolsets. In one of the demonstrations, 30 different software systems were integrated. The efficiencies realized were significant, but perhaps most significant was the creation of a full electronic design-to-production package. The value of TEAM's model-driven environment was successfully demonstrated in all of the projects.

Difficulties of Enterprise Integration

In a truly integrated enterprise, all of the tools used by all of the functions of all of the participants work together in a seamless fashion such that all required information is available in the right form to all of the users as they need it. To achieve this perfect solution, all systems and tools must comply with the same universally accepted standards. Because such universal interconnectivity and interoperability is clearly neither available today nor likely to be in the foreseeable future, TIME, in the same manner as TEAM, is striving to adopt an integration framework for the munitions enterprise that can serve as a liaison between all of the disparate systems and protocols and enable them to communicate (TEAM 1997).

Although the TEAM program considered its methodology to be a breakthrough for integrated product realization, it also recognized that this methodology was only part of the solution for a truly integrated enterprise. Product data management (PDM) for large, complex assemblies is a large undertaking and must be carefully managed. Scheduling and shop floor control issues must also be addressed. Indeed, integrated product realization is only one piece of the puzzle, albeit an important one.

Many organizations have a variety of databases, as well as new and legacy systems, all of which require integration to enable optimum organizational performance. To do this requires an integration framework or common environment (a software infrastructure having common objects, services, and interfaces) that enables plug-and-play interfacing and information sharing across all of the participating computing platforms and operating systems (TEAM 1997).

In its last year of operation, TEAM addressed these enterprise integration issues. The process of integrating the WIM with commercial PDM systems was initiated. The sharing of business data between ERP systems and the WIM was addressed. Progress was made, and these capabilities continue to be developed in the commercial sector. Although the WIM, as designed by TEAM, was a userfriendly tool for integration, it should be pointed out that the marketplace continues to mature and that commercial tools are now emerging that have demonstrated much of the same functionality that TEAM pioneered.

Other elements of technology that were not available commercially during the TEAM program are now becoming so. Some of these are described below:

- As a result of TEAM interactions, Cognition Corporation (Bedford, Massachusetts) brought to the marketplace a new tool called Knowledge Center, which captures manufacturing logic for design advisors and automated information systems.
- The Delmia Corporation Division of Dassault Systemes (then known as Deneb) entered into an agreement that is bringing to market a CAD-driven, expert-knowledge-based programming tool for inspection.
- Several organizations have sought rights for the feature-based tolerancing and planning tools.
- A new company called VEPortals has taken the WIM to the commercial market.
- Several existing tools were also enhanced and modified based on TEAM capabilities.

NETWORKING AND CONNECTIVITY

The TIME program has as a goal the creation of a network that will allow secure, interactive, multimedia communication between nodes, thus enabling a concurrent engineering environment. This network will be capable of transmitting complicated product design and process data from research and engineering to manufacturing environments and will enable the production and monitoring of ammunition at multiple sites. Each node will also be functional and capable of stand-alone connection to any other node in the TIME intranet or outside the intranet using commercial service providers directly without having to go through the centralized network (ManTech 1999).

Networking activities include the following efforts (Burleson 1999b):

- Designing a centralized network architecture;
- Procuring and implementing a centralized network and services;
- Managing the centralized network;
- Designing and installing collaborative communications cells;
- Evaluating, procuring, and integrating initial tools for office functions, concurrent design viewing and collaboration, video, and audio; and.
- Demonstrating initial concept capabilities.

The TIME program has created *TIME Centralized Network Architecture* (LCMS 1999), a high-level guideline describing principles and objectives for the network architecture of the program. The document identifies the high-level needs for networking connectivity and defines high-level standards, technologies, configurations, and processes that will support the network. The system described in the document is intended to evolve into a production network platform for the munitions industry.

The network described by the architecture document is to include an Internet-based wide area network, local area networks, servers, workstations, and network services. Connectivity between nodes will be established at five sites selected by the government. The goal of the TIME architecture is to define a network that is robust, reliable, secure, and scalable; that uses standard interfaces and protocols and shares resources; and that provides services in a cost-effective manner. The architecture emphasizes the use of COTS systems as well as open-standard protocols and file formats. The security architecture is defined to support an approach based on need-to-know. TIME intends to build on an evolving e-commerce paradigm using information technology (IT) standards such as data markup language, CORBA, and the Standard for the Exchange of Product Model Data; standard software; and brokers for component metadata exchange, messaging, and visualization. TIME program managers envision that budget realities will result in network deployment and interconnection over a period of many years. A demonstration of the TIME approach to the secure exchange of product data was conducted in 1999 between the Scranton Army Ammunition Plant and General Motors Powertrain. This demonstration project is discussed in more detail in Chapter 6.

The vision of the TIME program architecture document is to create a backbone into which virtually all communications and data functions can be connected. It is a vision of interconnectivity and interoperability. Connectivity involves the ability of multiple software applications, running on the same or different computer systems, to transfer information from one to the other and then take appropriate action using the transferred information. The committee knows of no government-owned/government-operated (GOGO) munitions manufacturing operations where the envisioned computer systems and software applications are in place. Indeed, they have yet to be specified and identified in a detailed plan by TIME. The implementation of connectivity cannot begin until these computer systems and software packages are specified, identified, and installed.

For most commercial operations with a typical level of technical support, just the selection of comprehensive, integrated computer systems and software is a complex and risky task requiring several years of concentrated effort. ERP systems are only as good as the information they process, the user definitions of where the information is needed, and the formats in which the information will be used. To create an appropriate information infrastructure, as-is information flows must be clearly documented, describing what information is processed, where it comes from, and where it goes. Human interaction and decision processes must be similarly documented, including what is done with the information and why. Even these basic, preliminary tasks take time and effort. In a medium-sized operation, they can involve hundreds of people. Often the information available to them and the resulting actions will conflict, requiring discussion to resolve these conflicts.

After the information and data are defined, it is necessary to determine how the information should flow and what results are needed by each department and function. Experts in IT must work closely with key personnel from all participating enterprises and functions during this period to evaluate options and optimize the system. Appropriate commercial hardware and software systems must be identified, investigated, compared, and selected. Finally, this process of system definition, procurement, installation, and debugging can cause disruptions in an organization, so people issues must be considered.

The Army munitions enterprise, in contrast to most commercial operations, is very large. It starts with the deputy director of Strategic and Tactical Systems (Munitions)[2] in the Pentagon and extends through all of the arsenals and prime contractors, down their supply chains through multiple tiers of subcontractors. Fortunately, many of the commercial operations have already performed these tasks for their own operations and installed their own systems.

Recommendation: Because the high-level enterprise and network architectures have been defined for the integrated munitions enterprise, the TIME program should focus next on defining information requirements and flows and then defining the requirements for enterprise and supply chain systems.

Some of the methodologies and tools that TIME is endorsing for connectivity were originally identified by the TEAM program. Although TEAM successfully applied some of these methodologies in the design and manufacture of several types of sample products, they are still considered to be in alpha (initial) evaluation and will pose some risks until they are thoroughly validated. They may, however, help the Army with its integration task and should further validate the worth of the TEAM initiative.

Designing the system and selecting the components for extensive integration of computerized product development and business management tools is a major goal of the TIME program. It would be tempting to say that all computers in this enterprise system must be interconnected. That might be a good technical measure, but experience has shown that it is not necessarily a good predictor of system success. Careful study of successful integration programs reveals that it is not often the physical connection of computers that gives the greatest benefit or the lack of physical connection and associated software that causes the worst problems. Thus, the percentage of interconnections may be a poor metric for the success of the TIME program.

The attraction of total system interconnection is that information can be moved from one place to another quickly. The disadvantage of massive interconnection is often its cost. It is sometimes possible to avoid a lot of cost if slight delays in information transfer can be tolerated. For example, if it takes a millisecond for a sensor to tell a milling machine controller that the cutter has broken, that is acceptable performance. If it takes a minute, that is unacceptable performance. But if a manufacturer is informing a supplier that next month's

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[2] This office reports to the Undersecretary of Defense (Acquisition, Technology, and Logistics).

shipping requirements will be increased by 10 percent, there is little difference in value between a delay of a millisecond and one of an hour.

For example, an electronics manufacturer in Ohio wanted to more closely integrate the scheduling of its assembly operations with those of a company that supplied their parts. The two companies saved over $100,000 on the project by not connecting their computers together. Instead, after each master schedule meeting, the assembly superintendent faxed his notes on the assembly schedule revisions to the supplier, who interpreted the changes and adjusted his parts delivery plan. The two were well integrated but their computers were not connected. From a business viewpoint, TIME should be evaluated by determining whether information moves as fast as is useful or necessary, not by whether computers are physically connected. Cost-benefit analyses can be extremely useful in the regard.

Recommendation: The TIME program should perform appropriate cost-benefit analyses for each system interconnection for purposes of creating a cost-effective system and to establish priorities for required interconnections. Cost-benefit analyses should also be performed for software integration and for data integration.

Many essential networking and connectivity details have yet to be addressed by the TIME program. For example, large organizations, including the DoD and major corporations, are creating increasingly complex firewalls to inhibit hackers and to guard proprietary information. The TIME program will need to make a major effort to define and implement systems that allow its communications to move through the disparate, evolving firewalls of the participants while not compromising the security of their proprietary information.

ASSESSMENT OF ENTERPRISE INTEGRATION

The TIME program is facing a substantial challenge in attempting to define the high-level architecture needed for a very large, diverse, and complex integrated enterprise. Most enterprise integration efforts to date have involved the integration of functions within individual enterprises, perhaps at multiple, geographically dispersed divisions and often having a variety of new and legacy operating systems. Some enterprises have gone a step beyond and have begun to integrate their supply chains.

The TIME program is attempting to take enterprise integration to yet another level. It is attempting to define a system for managing the Army munitions procurement enterprise. This system must, in turn, be interoperable with the following systems:

- Numerous other existent and future DoD operating systems, such as payroll and logistics;
- Still-to-be-developed operating software that will be required at the Army's GOGO arsenals and munitions plants;

- Present and future enterprise management systems and supply chain management systems at prime munitions manufacturing contractors, as well as such systems at all of the contractors' suppliers and, in turn, throughout the multiple tiers of each supplier's many supply chains;
- Present and future enterprise management systems and supply chain management systems at all dual-use contractors that will be used for replenishment, as well as such systems at all of the dual-use contractors' suppliers and, in turn, throughout the multiple tiers of each supplier's many supply chains.

Thus, the enterprise, network, and data architectures must be capable of defining a path for the simultaneous integration and interoperability of many hundreds of systems, each of which is subject to periodic upgrades or replacement by their primary users.

Creating a truly integrated enterprise has proven to be a daunting task for many commercial manufacturing enterprises. Newspapers and trade publications have, for the past several years, printed numerous stories about enterprises large and small, many of them reputed to be very well run, that have undergone massive struggles in their attempts to integrate their enterprises using COTS ERP systems. Some of these enterprises have given up completely after huge expenditures of resources. Additional challenges have been encountered by enterprises attempting to integrate their supply chains using COTS supply chain integration software and COTS CAD/CAM systems. In short, the creation of an integrated munitions enterprise will involve several layers of complex challenges:

- Working with COTS ERP and supply chain management systems that, for the most part, have themselves yet to be thoroughly validated;
- Achieving successful interconnections and interoperability between evolving, disparate systems used within enterprises;
- Integrating such systems among the enterprises, both corporate and government, in supply chains;
- Bringing GOGO facilities up to date in these capabilities; and
- Selecting and implementing an Army munitions ERP system that must be (1) tied to other DoD systems, and (2) integrated with all of the conventional munitions industry's GOGO, GOCO, research labs, and prime contractors, as well as all of their supply chains.

The TIME program is attempting a very large enterprise integration effort. Furthermore, funding to date has been sufficient to support technology demonstrations but not full-scale integration across the MIB. The committee is impressed by the enormity of the enterprise integration task being addressed by TIME.

As the committee reviewed the enterprise and network architecture documents, which are well designed to provide high-level guidance for integrating the munitions enterprise, one fact became clear. Because TIME is embarking on the creation of a massive and highly complex supply chain, the addition of technical approaches for management and integration of supply chains to the architecture documents would be most worthwhile.

Supply Chain Management

A large part of the enterprise integration effort of the TIME program will properly fall into the category of supply chain management. “Supply chain” is a term increasingly used by logistics professionals to describe all of the efforts associated with producing a product, from the ultimate customer (in this case the war fighter) to the extraction of raw materials, and all of the process steps and supporting functions in between. Thus, in the case of the munitions industry, the effort includes product design and development; assessment of routine inventory requirements and potential replenishment requirements; management of both routine and potential surge capabilities for manufacturing and assembly; stockpiling of raw materials and parts; warehousing of finished product; order entry and management; and distribution and delivery to stockpiles and the ultimate users.

Efforts to optimize, integrate, or manage the performance of a supply chain typically focus on assessing the value added by each step and function in the supply chain rather than on the overall performance of the individual enterprises. Thus, “supply chain management” can be defined as “A business strategy to improve shareholder and customer value by optimizing the flow of products, services and related information from source to customer” (Warner et al. 2000). An “integrated supply chain” can be defined as “an association of customers and suppliers who, using management techniques, work together to optimize their collective performance in the creation, distribution, and support of an end product” (NRC 2000). Thus, in the approaches being implemented by leading major companies today, each participant in the supply chain is expected to optimize its effort so as to achieve overall improvement in the cost of the finished product and responsiveness of the supply chain to evolving customer needs. All of the participants must be aware, ideally in real time, of changing customer needs and delivery requirements, as well as changes in the operating conditions and capabilities of all of the other participants. Thus the right quantities of goods and services can be made available at the right times and places throughout the supply chain without creating excess inventories or the need for excess manufacturing capacities.

According to an analysis by the Gartner Group, companies that invest in the integration and management of their supply chains can expect to achieve the following business improvements (Kulkarni 2000):

- 150 to 250 percent increase in profits,
- 30 to 70 percent reduction in order cycle time,
- 5 to 25 percent improvement in customer service levels,
- 10 percent reductions in inventories,
- 600 percent increase in inventory turns,
- 25 to 30 percent increase in distribution personnel productivity, and
- 50 to 60 percent reduction in errors made in trying to predict demand.

These types of business improvements can result in dramatic reductions in cost and enhanced response to customer needs. For example, Dell Computer Corporation's dramatic success in the highly competitive personal computer industry was made possible, in large measure, by its focus on the management of its supply chains (NRC 2000).

Strategically managing the supply chain to reduce total costs and to optimize the availability of materials and process capabilities is a central focus of TIME. Determined to pay the lowest possible price for goods and services, both defense and commercial customers have traditionally attempted to maximize competition and have negotiated hard for concessions on price, inventory stockpiles, and delivery. In many cases, especially in the defense industry, this has weakened suppliers and reduced the industry's interest in serving defense needs.

In contrast, modern supply chain management techniques recognize that adversarial relationships between customers and suppliers are not necessarily in the customer's best interests, and instead they emphasize win-win relationships between customers and suppliers. Benefits to the customer can often be maximized by nurturing of long-term relationships, even if the supplier skill sets are only used on a contract-by-contract basis. Such partnership approaches can require supply chain participants to change their attitude from the traditional attitude: What's in it for me? to a new attitude: How can we maximize our common good, and what can I do to help us achieve our mutual goals? This change in philosophy can be extremely difficult to accomplish, especially in defense industries, and cannot be created merely by negotiating legal contracts. It requires trust and a spirit of giving, both of which are difficult to develop in competitive industries, where companies may be fighting for their very survival. In the defense industry, developing these cooperative relations and optimizing supply chain performance for the mutual benefit of all participants are in many cases made more difficult or not allowed by Federal Acquisition Regulations and contract law, both of which flow down fiduciary responsibility (i.e., each supplier is directly accountable for its portion of the work as defined in the contract or purchase order) (NRC 2000, pp. 14–15).

Recommendation: The Army should follow the current industrial practice of developing long-term mutually beneficial relationships with both its routine munitions suppliers and its replenishment suppliers. It should also take advantage of changes in government procurement regulations to optimize the performance of its munitions supply chains, especially when needed for replenishment.

One of the key principles of supply chain optimization is the implementation of technologies that support multiple levels of decision making and provide a clear view to all participants of the flow of products, services, and information. Such a system must be able to handle daily transactions, schedules, and e-commerce across the supply chains and thus enable short-term balancing of supplies, inventories, capacity utilization, and demand among participants. It must also support longer-term planning, scheduling, and investment in resources and capabilities. Most important to the munitions industry, it must support strategic planning and an integrated network model capable of synthesizing data for use in high-level “what-if” scenario planning and capacity assessments.

To date, few corporations in commercial industry, despite huge investments in technology, have succeeded in acquiring and extensively deploying a full complement of these capabilities. According to a late-1998 Grant Thornton survey, only 11 percent of all manufacturers, mostly the largest ones, have adopted ERP. Among mid-size ERP users, only 43 percent reported that their integrated IT system was fully functional (Braunstein 1999). Major problems have included system defects, difficulties in redesigning business practices to conform to the systems, and difficulties in interoperability between systems (e.g., enterprise management systems and supply chain management systems).

ERP systems, which typically focus on the internal systems of one corporation, such as planning, production, and finance, alone are not sufficient, as they generally cannot provide the bridge between the multiple systems of suppliers and customers that is required for dynamic scheduling and inventory optimization. Hence, participants must look beyond ERP to supply chain management systems capable of integrating the entire organization. ERP vendors such as SAP, Oracle, and Baan[3] are increasingly developing supply chain management modules and are assisting in integrating with third-party solutions.

Supply chain management systems by vendors such as Manugistics, i2 Technologies, and ProMIRA are finding increased acceptance. In many cases, substantial improvements have been made in operations within individual corporations (enterprise management), and to a lesser extent the performance of supply chains has been improved, primarily in the areas of inventory reduction, order integration, and logistics. However, tremendous opportunities still exist in commercial industry for the improvement of enterprise operations, supply chain operations, and the synergy that can be created by developing a system of systems as these disparate, complex systems and their interoperability are improved and more extensively utilized.

This discussion of the shortcoming of COTS enterprise and supply chain integration systems should not in any way be interpreted as a message that the efforts of TIME should be abandoned. Quite the contrary, TIME, if properly executed, offers the potential for huge savings to the taxpayer and dramatic improvements in the responsiveness of the munitions enterprise to U.S. defense needs, but the challenge should not be underestimated.

Problem Definition

Although creation of high-level architectures can serve to define and guide the enterprise integration efforts, one of the critical next steps is the appropriate definition and documentation of the existing munitions industry. This will be critical because the steps in creating the enterprise will properly start from the bottom and will only later be integrated at high levels. The TIME program must, for instance, thoroughly understand the current munitions industry. The capacity and the

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[3] Vendor names are provided for purposes of example only and do not constitute a recommendation by the committee or the National Research Council.

capability of all government and commercial munitions plants and how long it will take to activate various capacities must be entered into a common database. Prenegotiated dual-use capacities must also be entered into the database along with scenarios for workforce recruitment and training.

For this approach to be viable, it will be necessary for DoD to negotiate agreements with potential replenishment suppliers and to establish an assessment of the capabilities of the MIB. The TIME program should avail itself of this information, assist in keeping it up-to-date, and assist in getting it stored in a format compatible with the TIME enterprise architecture, so that it is readily accessible by participants in the integrated enterprise that have a need to know. This database should serve as a foundation for TIME's efforts to integrate the enterprise and should prove useful in establishing program priorities.

Another example of problem definition faced by the TIME program is that of precisely defining its objectives in communicating with the shop floor. According to Keith Nosbusch, president of Rockwell Automation Control Systems, the capability to communicate from the Internet to the shop-floor control and to remotely monitor and control the shop floor is already available, but, except for hazardous processes such as refinery operations and energetics processing, no one wants to do it (McCormack 1999). From his perspective, this capability is not going to be extensively implemented in the near future because resolving the question of who gets to make changes on the shop floor and how they are to be controlled represents both a culture shift and a security and safety shift. Control of changes is a far more substantial issue than remote monitoring and diagnostics, which are real capabilities that are implemented today in a variety of commercial industries. To give a controls engineer at the Armament Research, Development, and Engineering Center, for example, the capability to make changes on the factory floor of a remotely located commercial supplier is not likely to be accepted by commercial participants in the munitions supply chain for the foreseeable future. Remote monitoring is far more likely to be accepted. Presentations to the committee by participants in the TIME program have failed to make clear the extent to which the program intends to implement these capabilities. The committee believes that it is important that the TIME program present a clear, consistent picture of its intent on important issues such as these. Furthermore, although the committee is supportive of efforts to use COTS technologies to monitor the status of munitions manufacturing operations and inventory levels, especially in times of national crisis, the committee believes that remote control of all but the most hazardous operations represents unacceptable safety risks to shop floor personnel and damage liability to the U.S. taxpayer.

Details of Enterprise Integration

The high-level architecture is described quite well and appears to the committee to be a solid, state-of-the-art approach. However, no details have been provided about how it will be integrated. This is a significant weakness of the program. The TIME program must take steps in the near future to define its enterprise integration methodology (business-to-business) and to devise a means for modeling the integrated system. Although not the highest priority for TIME during the next several years, dynamic modeling will be required to test the behavior of the system under many conditions.

The following elements remain to be well defined in the context of the enterprise architecture as part of the integration effort:

- Role of the enterprise infrastructure;
- Role of integration hubs;
- Role of extensible markup language (XML) as an integration methodology for enterprise-level information exchange;
- Middleware for integration, including message-oriented middleware;
- Details regarding enterprise-level database integration;
- Communication technologies for middleware integration, such as CORBA or the Distributed Component Object Model;
- Role of information brokers in enterprise integration; and
- Role, if any, of online trading techniques.

Concluding Discussion

The TIME program correctly views the enterprise as a constantly changing and dynamic environment. However, there are no provisions in the approach for understanding its dynamic nature and characteristics. No tools or methodologies are identified to discover and evaluate the available enterprise-level static and dynamic capacity and capability. In addition, the TIME program should outline a bridge or roadmap between the present state of the munitions enterprise and the long-term vision of TIME. With the completion of the initial high-level architectures, the TIME program has correctly determined that a next key step is the assessment of the capabilities of the munitions industry and its multitiered suppliers, to determine which pieces of the integrated enterprise are already in place and which specific pieces will be needed (McWilliams 2000b). Prioritization must come next.

The TIME program has done a good job of developing the vision and describing the enterprise architecture and its components. However, it is the committee’s view that very little effort has been put into clearly outlining the details of the TIME integration methodology. Integration of the extended enterprise must, due to budget constraints, be implemented in a well-prioritized, cost-effective manner so as to create the maximum benefit for U.S. security for the taxpayers’ investment.

New approaches are emerging that could affect the way an enterprise can be integrated. Value stream analysis (Hines 1999) is one such approach, in which value streams are defined across enterprises and then integrated. The development of XML and its ability to define extended private tags is an example of an emerging technology that can facilitate enterprise integration. Development of integration hubs is another. These approaches are maturing at a rapid pace and may be available for COTS use in the near future.

Conclusion: The TIME enterprise architecture document presents a high-level vision for the integrated munitions enterprise. However, the program provides little insight into detailed operational characteristics and selection criteria for key components. TIME must prepare detailed plans for networking and interconnection of the myriad systems that will make up the integrated enterprise.

The magnitude of the integrated enterprise must be kept in context. Its completion, as presently envisioned, can require a massive investment. In contrast, the TIME budget is adequate only for technology demonstrations. It is, therefore, only reasonable to assess the plans of the TIME program against standards for current practice in management of industrial supply chains in large organizations. It is the opinion of the committee that TIME is identifying and attempting to demonstrate the use of integration tools that are consistent with current enterprise resource management directions and emerging integration architectures while offering cost-effective views for integration of manufacturing operations. These tools are being used in demonstration projects, which can serve as an effective way to influence the funding and direction of the program. These demonstration projects also serve to create a focused intensity and unity of purpose within the program that cannot be achieved in any other way. The committee believes that this is a good strategy and that the Army should understand it and reinforce its effectiveness.

There are enough commercial systems of sufficient capability on the market today to enable the TIME program to begin to create the munitions enterprise of the future. However, the tools required to enable these systems to function in an interoperable manner in an integrated enterprise are still lacking in some ways, although appropriate commercial tools are being developed at a rapid rate. The Web Integration Manager, selected by TIME, is an excellent example of such a tool. The emphasis of the TIME program should be placed on defining and prioritizing needs; identifying the appropriate interoperable toolsets; and beginning its implementation at low levels, based on an appropriate prioritization process that identifies critical capabilities and assesses returns on investment.

Recommendation: The enterprise integration effort should begin with well-defined, high-priority low-level work. For example, standardized databases containing supplier and subsupplier capabilities and capacities should be developed and kept updated. This includes the workforce skill base, not just the manufacturing base. A PDM system is essential. The focus of the efforts should be on integrating people, business practices, and partner relationships, not just on computers and networking.

The committee recognizes that the costs of implementing the integrated munitions enterprise will be high. Although major commercial participants typically will have invested in their own systems that can be networked into the TIME architecture with little cost to the government, many small participants cannot afford such capabilities on their own. Some large contractors, such as Lockheed-Martin, have solved this problem by negotiating large licenses with vendors of systems such as CAD and then giving small participants in their supply chains free seats so that they can concurrently participate in product development (Morris 2000).

GOGO facilities have no such capabilities, and many small participants in the munitions industry supply chains probably have few of these capabilities. Thus, implementation, which can include significant costs for site licenses, hardware, employee recruitment and training, communications and interoperability capabilities, and system validation, can add up to a significant investment by the taxpayer. In establishing priorities for implementation, DoD should look across the entire spectrum of munitions needs, from ammunition to smart munitions, and place priorities on those segments of the industry that are most critical to future national needs.

3

The Approach to Munitions Replenishment

INTRODUCTION

Reduced worldwide demand for munitions in the 1990s has had a dramatic impact on the U.S. munitions manufacturing industrial base. In a national emergency, requirements for munitions may rapidly increase by an order of magnitude or more. Such events may require significantly more production facilities and resources than are currently available to satisfy requirements. According to reports by the National Defense University (NDU 1996, 1997, 1998), although the United States remains the world leader in munitions technology, the nation's ability to rapidly produce high-technology weapons on a large scale has diminished. Over the 3-year period from 1996 through 1998 the reports are increasingly strident on this issue.

MUNITIONS REPLENISHMENT POLICY

During the Cold War, munitions planning strategies designed to address the potential threat of major conflict relied heavily on domestic surge production and mobilization capacity. In response to perceptions of reduced threats, the Department of Defense's (DoD's) current policy places greater reliance on the ability of the existing stockpile to meet munitions requirements for the armed services of the United States and its closest allies through two near-simultaneous major regional conflicts. This policy seeks to leverage the firepower of the stockpile through gradual acquisition and deployment of precision-guided, smart munitions. Current policy stipulates that the munitions stockpile, with routine production, must be able to meet peacetime needs (training, testing, and replacement of obsolete munitions; sales to foreign governments; and weapons upgrading) and support two near-simultaneous major regional conflicts. When conflicts occur, munitions stockpiles may be drawn down to the point at which large orders for replenishment are placed and the routine manufacturers are unable to accommodate the surge in demand within their own organizations. When that occurs, the policy stipulates that the munitions manufacturing base must be capable of replenishing the stockpile following those conflicts within 3 years (GAO 1996a). Under this policy, there is no longer a requirement to surge the munitions base during conflicts.

In implementing this new munitions planning strategy, DoD has been seeking to divest itself of munitions plants, equipment, and labor by closing down some operations and by transferring other selected assets to private industry. It has proven challenging to achieve the transfers in an economically feasible manner, that is, in such a way that it can be at least somewhat profitable for the commercial operators (NDU 1997). One of the approaches to increased profitability being considered by the Totally Integrated Munitions Enterprise (TIME) program involves scaling munitions facilities for continuous runs at variable production rates. This could be accomplished, for example, in facilities designed for highly flexible production in which the equipment and workforce have alternative commercial uses.

TOTALLY INTEGRATED MUNITIONS ENTERPRISE REPLENISHMENT STRATEGY

The TIME program's strategy for supporting DoD's new replenishment policy is to use modern manufacturing technologies to create a flexible base for munitions manufacturing. Peacetime needs will be met by means of routine production using the organic base. Stockpile replenishment following a regional conflict will be achieved in the following sequence (PNNL 1997; McWilliams 1999): (1) utilize commercial capacity first; (2) utilize warmest (most readily reactivated) organic capacity next that most closely matches the need; (3) if necessary, activate cold (laid away) organic capacity.

This strategy calls for products to be concurrently produced at multiple locations (both organic and commercial) to meet peacetime and replenishment requirements. There are implicit assumptions in this strategy. First, it assumes that there exists a set of commercial firms willing and able to maintain dual-use production facilities that are normally used for commercial production but are capable of being rapidly converted to munitions production. Second, it assumes that an enormous amount of data (product requirements, engineering designs and processes, machine tool numerical control programs, production control instructions, quality and safety requirements, etc.) can be communicated accurately and in a timely manner between the Army, the Armament Research, Development, and Engineering Center, and commercial and organic manufacturing sites.

TIME's approach to the replenishment (as opposed to routine production) of metal parts and electronic components relies heavily on the prenegotiated conversion and ramp-up of dual-use manufacturing capacity at producers of commercial products. For energetics production, TIME anticipates scale-up of commercial munitions suppliers. The TIME program intends to facilitate this use of commercial suppliers by improving communications between Army facilities and replenishment suppliers. Using the TEAM methodology to interface Army computer systems with those of suppliers, TIME will develop procedures for assuring the timeliness and quality of supplier production.

It is intended that the Army be able to download production processes and remotely monitor or control the supplier's machine, as required. The Army would be able to direct the machine to execute a series of actions up to and including the machining of standard test pieces. These moves and test pieces can be measured on the machine with machine-mounted probes and the results can be sent in real-time to the Army. TIME anticipates that by downloading the latest dimensions and processes directly to the machine controller, the probability of high-quality initial production under replenishment conditions can be substantially enhanced. Finally, when first-article inspection is carried out on the supplier's coordinate measuring machine, the results can be reported simultaneously to the Army. During production, routine sampling inspection results are similarly sent to the Army in real time.

The TIME program anticipates that the normal steady-state munitions producers will not be able to accommodate all of the replenishment requirements within their own organizations. Therefore, manufacturing technologies (designs and processes) must be transferred rapidly to other manufacturers who typically have agreed in advance, in return for consideration, to make some or all of their production capacity available in times of need. Most of this equipment will ordinarily be used for commercial production, although some may stand idle until needed. The replenishment manufacturer may, or may not, have substantial experience in munitions production.

CONCERNS REGARDING REPLENISHMENT

In assessing the TIME program's approach to replenishment, the committee used several perspectives from commercial industry, including a technology transfer approach and a supply chain management approach.

Commercial Manufacturing Environment in the Year 2000

The TIME program is driven by both the ongoing need for conventional munitions and the need for emerging sets of smart munitions and advanced energetics (explosives, pyrotechnics, and propellants) that will increasingly be used in future conflicts. The problem that TIME addresses—the assured supply of parts and assemblies—is not unlike the challenge faced by all commercial industries. The trend in modern manufacturing is to focus on core competencies, while outsourcing production of components not identified as part of the company's core competency. This has led to a large increase in the importance of relationships with suppliers; this set of relationships is called the "extended enterprise." Indeed, TIME is the Army's recognition of the need for a ready, healthy, technology-enabled, extended munitions enterprise.

As a general premise, there is no need for the TIME program to be a cutting edge technological leader in modern manufacturing. Commercial industry is moving rapidly and the munitions industry can be vastly improved merely by using the increasingly effective tools being deployed in the commercial sector. Narrow manufacturing technology gaps may appear, primarily as they relate to military-specific munitions industry requirements. It is in these gaps that TIME will need to make an innovative technological contribution, and it is important that TIME work continuously to identify and resolve these gaps.

Numerous up-to-date, commercially proven technologies will be needed, including state-of-the-market information systems that can introduce efficiencies into the supply chain. This level of capability does not broadly exist in the organic munitions industrial base today. Most of the manufacturing processes within the organic facilities are not equipped to operate in such an interactive environment. Much of the design and process data for conventional munitions exist on paper drawings or are not documented at all. The Army is in the process of scanning the paper drawings into electronic databases, though in most organic munitions manufacturing facilities the computer capabilities required to access and use these databases are limited or nonexistent. Their communications networks are totally inadequate to support these requirements.

Conclusion: The committee has concluded that many of the fundamental elements required to support the DoD munitions replenishment policy are either not adequate or not in place.

It would be helpful for the Army to classify its existing munitions into the following categories: (1) those that are most critical for the foreseeable future, (2) those that are not as critical but will still need to be supported for some time, and (3) those that can be declared obsolete.

The systems currently required to support each munition need to be documented. This documentation should include data such as (1) whether product information is on paper drawings, 2-D CAD, or 3-D CAD; (2) whether processing data are available; and (3) what, if any, specialized equipment is needed to manufacture the item. This information could then be used to determine which of the munitions are supportable based on considerations such as the following: (1) Data are usable as is, and replenishment participants are available with supporting systems, (2) Data must be translated to a new system because of obsolete existing equipment, (3) Data are not available and must be created or restored.

The results of this analysis would provide the basis for making decisions regarding preferred data and processing systems to be required of the supply chain. When current systems are no longer supportable, a decision would be made to convert to a preferred new system, considering transferability of the existing product data. Once preferred systems are defined for existing munitions support, the expansion of the preferred system could be considered for new product realization but with the requirement that the additional systems would not cause a proliferation of systems that might have limited value and compatibility.

Remote Operation of Equipment

Although it is technologically feasible to remotely operate equipment, implementation of such operation requires extensive safety interlocks to prevent damage or injury. Such remote operations are typically found in continuous process industries, such as power plants, chemical plants, oil refineries, and processors of energetic materials. Typically, these are operations in which, for safety reasons, few or no operators are present on site and it is cost-effective to automate the processes. In the opinion of the committee, it is unlikely that remote operation of machine shops will become accepted practice as long as operators must be in the vicinity of the equipment to perform operations such as loading or unloading of parts and are thereby subjected to the risk of unexpected motion of the machine.

Agile, Lean Manufacturing

One of the cornerstones of the TIME program is its reliance for replenishment on contracts with commercial corporations with dual-use production capabilities. Many of these companies are, in accordance with current business trends, evolving to perform only specialized (and limited) functions in the manufacturing supply chain. Thus, the TIME program must be nimble in building relationships with manufacturers whose definitions of core competency are evolving. The original agile manufacturing vision adopted by these companies stated that as opportunities or needs arose, they would rapidly move into and out of associations with other companies. The reality is that the coupling and uncoupling of enterprises is proving to be more difficult than originally thought.

One reason is that this vision ignored the value and importance of long-term working relationships, contract performance, and issues of trust. Corporations, to the extent possible, are risk averse. Although proprietary design and financial data must be shared in modern supply chains, companies still go to great lengths to guard their proprietary information and intellectual property. Business-to-business information systems capable of supporting agile, lean manufacturing are becoming available but are not yet universally used. Once communications, working relationships, and trust have been established, there is reluctance to change suppliers unless the supplier is not capable of performing as new products are developed and enter production.

For example, in the automobile industry, there has been a concerted effort to limit the number of suppliers. At the same time, there has been a concerted effort to qualify the remaining suppliers so that accepted norms for quality of product are ensured. In addition, some responsibility for component design has been delegated to suppliers. The result is fewer suppliers and fewer changes in suppliers. Likewise, in the munitions manufacturing industry, the same phenomena are supporting a reduction in the number of suppliers and a solidification of working relationships along the supply chain. The shrinking global market for munitions is accelerating this process significantly.

A driving force in the enterprise-splitting process is the desire of original equipment manufacturers (OEMs) or prime contractors (typically design, assembly, and marketing companies) to limit risk. In the enterprise splitting process, risk is placed directly on each independent element of the manufacturing supply chain. Thus, in an agile, lean manufacturing world, survival of the fittest becomes much more focused. Weaker elements of the manufacturing chain that historically were protected by stronger elements within the vertically integrated corporation are no longer protected. Once the entities become separated, each element of the manufacturing supply chain is forced to rise to a competitive industry standard or be eliminated. While issues of trust and communication often slow the process, competition results in continual pruning of the overall manufacturing enterprise. Successful survivors of this competitive process tend to be lean, having maximized their returns on capital. They are not able to maintain great amounts of surge capacity and still compete effectively in the marketplace. Thus, some dual-use military manufacturing capacity (and capabilities) may not survive the outsourcing integrated-enterprise movement unless protected or subsidized by the government. For example, during Operation Desert Storm, the United States found itself dependent on Japan to supply certain computer chips that were not available domestically. If this trend continues, the United States will become far more dependent on its allies for critical manufacturing capabilities. This situation may not serve the best interests of the nation, however, and it may be necessary to find acceptable alternatives considering risk, availability, and cost.

Simply put, competitive requirements for increasing supply chain efficiency will force a closer match of capacity with demand in the modern manufacturing environment. The cost of maintaining excess capacity dedicated to munitions replenishment, unless it is supported artificially, will make firms in the modern manufacturing environment less competitive than their leaner peers. Thus, it is likely that DoD must increasingly depend on preidentified dual use manufacturing capacity for replenishment. This may result in a substantial challenge for the TIME program and greater commercial economic dislocations and impact in times of crisis. Given the age of much of the equipment in the current munitions industrial base (MIB), planning for modernization and for activation of dual-use manufacturing capability needs to include identification of substitutes for specialized equipment in the current MIB, where alternatives are not currently available in the event of failure. It is within this environment that the TIME program must negotiate a dependable replenishment capability.

Recommendation: The TIME program should (1) create or update detailed plans to meet the DoD replenishment requirements, including the types of machinery required to do the job for the foreseeable future, and (2) update surveys or inventories of capabilities of the existing munitions industry and potential replenishment participants and keep these surveys up-to-date.

Replenishment as a Technology Transfer Problem

The rapid transfer of technology from routine producers of munitions to dual-use and mothballed replenishment facilities and their suppliers is critical to the TIME program's approach to replenishment. The committee defined "technology transfer," for purposes of replenishment, as the process by which designs, processes, data, knowledge, and other information used in the routine production of munitions are transferred to replenishment facilities and their supply chains.

Technology transfer in commercial industry is typically a difficult, expensive, and complex process that can be fraught with risk, especially if timelines are critical. Factors that can impede or hinder the successful transfer of technology can include the following (Cooke and Mayes 1996):

- Lack of technological awareness, knowledge, and support;
- Lack of funds;
- Conflicts of interest due to potential impacts on the competitive positions of the participants;
- Lack of trust;
- Poor communication;
- Lack of appropriate equipment and infrastructure; and
- Lack of time to complete and validate the transfer.

In the context of absorbing new technology, knowing why a particular technology works is often as important as knowing how to make it work. Because technology transfer can depend on the transfer of knowledge within the specific context of the adopting facility, an understanding of the reasons for a particular technological choice can be essential for successful implementation. This also implies the need for strong understanding of the processes being transferred in the routine munitions production organizations endeavoring to transfer technology (NRC 1995).

Because much technical know-how is typically unwritten and difficult to document, successful technology transfer may require extensive person-to-person contact, often involving the transfer of personnel from the sending to the receiving organizations for extended periods. The committee believes that this situation is likely to pose a serious challenge in the event that replenishment is required because (1) due to low ongoing rates of routine production, there are few remaining munitions manufacturing experts; and (2) their expertise will be required to ramp up their own facilities during the crisis. Developing expertise in some aspects of munitions manufacturing can be time-consuming. Thus, the TIME program must find a way to retain a cadre of trained munitions manufacturing experts sufficient to support replenishment if and when needed. Without them, TIME program replenishment plans are a hollow exercise.

Because surprises that can lead to cost overruns frequently occur during the process of transferring technologies, sufficient funding must be made available to cover these unanticipated events. Budgeting for unanticipated costs can be difficult within the federal budgeting process, so the TIME program must (1) be prudent in properly anticipating technology transfer and production start-up costs, and (2) write replenishment contracts in such a way as to minimize disruption of the technology transfer process due to concerns about funding when unanticipated problems arise.

In spite of the problems associated with technology transfer that are discussed above, the committee believes that, due to the likelihood of a compelling sense of urgency and the overriding importance of success in the event of a need for replenishment, many of the challenges that typically occur during commercial technology transfers are unlikely to be significant problems. Typical challenges include lack of trust between organizations, resistance in the receiving organization to the new technologies because they were “not invented here,” and clashes between corporate cultures.

A definitive plan of deployment (and demonstration) of the technology associated with technology transfer is needed for all critical munitions. A complete, detailed plan for technology transfer has yet to be formalized by the TIME program, an exercise that is likely to reveal the magnitude of munitions industry challenges in this area.

Labor Force for Replenishment

There are several categories of munitions manufacturers: (1) those who manufacture on a routine basis and, in the event of a national emergency, will ramp up as rapidly as possible; (2) the “laid away” or “cold” base (which consists of existing plants that are not currently in operation); and (3) those who manufacturer commercial products on a routine basis using equipment (such as lathes, milling machines, and punch presses) that can be considered dual-use (usable for both commercial and defense needs). The latter will, by prior contractual agreement, convert their productions from commercial to defense work in the event of an emergency. The operators of such dual-use equipment will already be using most of the skills required to build defense parts in the course of their daily work making commercial products. Their specific skills will, in some cases, need to be upgraded or broadened to meet defense needs. The latest specific dimensions and processes for defense parts will be downloaded to the dual-use manufacturers from the routine production houses. The rest of the information must come from in-house databases, learning packets, or previously trained operators. The bigger challenge lies in finding and training new workers hired for scale-up.

An agile workforce, including both the experts to successfully transfer manufacturing technologies and the expanded workforce to produce munitions, is important for achieving the readiness goals of the TIME program. A critical component of agility is the ability of the workforce within an organization to maintain existing knowledge and to rapidly acquire new knowledge as circumstances change. Methods must be developed for assessing workforce readiness within the integrated munitions enterprise. Readiness must be assessed from several different data sources, but all data must be synthesized into easy-to-understand metrics that can be monitored. This assessment must be contextual to fit the different needs of those within and outside the TIME organization.

State of the Art

Readiness of the workforce in a munitions enterprise organization can be defined in terms of skill sets. The needed skill set consists of the collective skills of the workforce needed to accomplish the tasks of replenishment. The current skill set consists of the collective skills currently possessed by the workforce, that is, (1) the skills of workers performing routine munitions production, (2) the skills of workers routinely operating dual-use equipment for commercial applications, and (3) the skills (probably limited) of workers in other segments of the labor pool that will be recruited in the event of a replenishment scenario.

The committee assumes that the present munitions workforce will be expanded in times of replenishment so as to meet DoD needs and, if possible, to simultaneously maintain limited commercial production. The committee also assumes that new workers will arrive with a limited skill set relative to that needed for munitions production. The difference between the needed and current skill sets represents an “organizational learning gap.” Participating organizations must be able to bridge their learning gaps efficiently under replenishment conditions through training, use of archived documentation, accessible training programs, or structural changes. Structural changes usually involve reorganizing or increasing communication channels. The state of the art can be evaluated in terms of existing tools and theories that already have or could affect developments and procedures in this area.

Organizational Learning

The overall construct for understanding the readiness of munitions manufacturing organizations can be in terms of organizational learning (e.g., Debenham and Clark 1994; Lewis 1997; Perneski 1992; Prytz et al. 1997). Most research on organizational learning has focused on either its characteristics (e.g., identifying features of organizations that exhibit the ability to learn) (Senge 1990) or structures (e.g., “warehousing” of knowledge in “experience factories” within the organization) (Basili et al. 1994). Both approaches are important for munitions manufacturing organizations. In particular, these organizations should be evaluated to determine if they have the structures and capabilities for learning. Warehousing knowledge should be considered especially important for replenishment organizations because of the long time periods between running the manufacturing lines for defense purposes. Easy access to the knowledge or experience will be important for readiness.

Needs Assessment Tools

Traditionally, the skill set required by an organization has been determined through needs assessments. A needs assessment is an evaluation of instructional requirements and is performed to identify, document, and validate gaps between what is and what should be and to prioritize the need to fill the gaps (Kaufman 1986). Needs assessments are typically performed at irregular intervals using paper-and-pencil questionnaires and face-to-face meetings. Low return rates on the questionnaires limit the effectiveness of the information received, and time and location constraints for face-to-face meetings lengthen the process.

An Electronic Performance Support System (EPSS) (Gery 1989; Raybould 1990; Reynolds 1993) is a specialized computer program that incorporates a variety of support tools designed to assist workers at their jobs and, thus, help organizations assess training needs. Usually, an EPSS includes an expert system, computer-assisted instruction, and databases. Electronic assessment tools, such as an EPSS, can be combined with on-line data collection and computer-supported cooperative-work components so that data can be collected quickly and continuously.

A needs assessment should result in job descriptions and a corresponding set of skills that the organization must possess in order to accomplish its goals. The gaps between the current skills and the needed skills must be identified. These gaps can be bridged through organizational learning if the knowledge is already resident in house or can be transferred in. A needs assessment, therefore, should also determine the skills that can be transferred to satisfy the needs. Part of the TIME program’s challenge should be to determine the most efficient means of transferring skills to satisfy the needs.

The munitions industry should use a database titled the Occupational Information Network, or O*NET, currently being developed by the Department of Labor (DoL 2000). This database describes over 1,100 occupations, can be used to locate occupations by skill requirements or key words, and has information on the transferability of skills. Proper use of the database can provide information on the organizational learning gap, efficient methods for transforming into the needed state of organizational learning, and time predictions for moving from the current skill set to the desired skill set.

Theoretical Approaches for Organizational Learning

Organizational learning and the current knowledge within an organization can be understood by using an analogy to human learning. Theories in the neurosciences (e.g., McClelland et al. 1995) state that knowledge exists within the neurons and synapses of the brain. Clusters of neurons, perhaps representing a concept or an object, are formed when individual neurons are connected by synapses. Learning occurs via repeated specific sequences of synapse “firings,” thereby establishing these connections between neurons. The synapse connections must be renewed continuously for knowledge to be maintained.

This “neuro-learning” model can be used to understand organizational learning. The “neurons” of an organization can be either the individual skills possessed by humans or external documentation (e.g., reports, technical specifications, electronically transferred files, etc.). Just as an isolated neuron in the brain that is unconnected to other neurons does not contain knowledge, an unread report, a never-used training program, and an individual with skills who is isolated within an organization do not contain organizational knowledge. Organizational "neurons" must be clustered and connected to constitute organizational knowledge.

Clusters of skills, and thus the knowledge within an organization, will occur when connections (the "synapses") are formed between the organizational neurons. Connections can occur at three or more levels: (1) person (one can assume that skills possessed by an individual are clustered and, thus, connected); (2) proximal locations (individuals with skills clustered in an office area have open communication channels, although they may not always be used); and (3) organizational networks (meetings, telephone, e-mail, intranets, and the Internet can be used to establish somewhat temporary connections between individuals).

A neuro-learning representation of the organization, such as this, provides a model that can be used to indicate how organizational learning occurs. The model indicates that knowledge in an organization can be created in two ways: (1) by creating new nodes ("neurons") with skills specific to the needs of the munitions manufacturer, and (2) by connecting existing nodes through "synaptic" relations to create knowledge from individual pieces of information from sources both inside and outside of the organization. In addition, this model indicates that "synaptic" connections will be destroyed if they are not used. In a replenishment-only (dual-use) organization, this is especially relevant because, in the absence of a national emergency, some of the training and skills of the workforce required for munitions manufacturing may not be utilized for long periods of time. Information is needed on how to maintain the "synapses," through integrated training programs, so that the organization can retain its knowledge in a cost-efficient manner. This is especially critical in a fast-moving technological environment in which even new knowledge becomes quickly eclipsed.

Theoretical Approaches for Representing Organizational Learning

Users, inside or outside the TIME organization, must be able to query the state of organizational learning and, consequently, the readiness of replenishment suppliers. Organizational learning must, therefore, be represented and quantified in database form such that multiple users can obtain the information they need without having access to information outside of their needs. Research on data cubes (e.g., Gray et. al. 1996), a concept developed in computer science, can be applied to the TIME database needs. Data cubes are typically used to represent commercial data used in decision support systems, also called on-line analytical processing. The cube is made up of cells, each of which records some numerical value of interest. The dimensions of the cube (any number, not just three as implied by the cube term) correspond to various orthogonal properties of interest. In terms of the skills represented in organizational learning, therefore, a data cube could be analogous to a "skill cube" (i.e., a multidimensional space corresponding to fundamental skills). The database should be constructed from information in the organization such as job descriptions; locations of employees; and existing clusters, networks, and communication channels.

Queries in data cubes are handled in interactive sessions in which users can “roll up” (i.e., move up the hierarchy along some dimension) or “drill down” (i.e., move down the hierarchy). These queries all involve aggregation of values stored in various sets of cells along different dimensions. The set of skills possessed by an individual can be mapped to a point or perhaps a small region in this multidimensional skill cube. The collective set of the points corresponding to the employees of a specific organization can identify the skills asset of the enterprise. Skill sets must be carefully designed, recognizing that content is more important than data manipulation. A single quantifiable value of organizational learning or knowledge would be an important and easy-to understand metric for monitoring and mapping the readiness of the organization over time.

Managing Workforce Maintenance and Development

The TIME program has yet to systematically consider workforce maintenance and development issues. Managers of the TIME program realize that workers in the replenishment plants may need a slightly different set of skills to manufacture metal and plastic components. Extensive training in safety and handling will be needed for those new workers processing energetics or packing and loading finished munitions. The committee is not aware that a needs assessment has been performed, or that the differences between needed and available skill sets have been identified, or that a program for acquiring the needed skills through recruitment and training has been layed out. The committee recognizes that there are no easy answers to questions such as how much training should be done now for skills that may not be needed for 10 years or may become obsolete. Managers within replenishment organizations and monitors from the Army need to assess the readiness of these organizations on an ongoing basis. TIME currently has no method for tracking readiness or determining the implications for readiness when workforce changes occur. An overall model of organizational learning is needed so that training can be rapidly implemented when needed.

Recommendation: TIME, as part of its replenishment plans, needs a human resources strategy that includes a recruitment plan, documenting and archiving of process details and required skills in anticipation of need, and well-prepared training plans that take advantage of up-to-date knowledge of how people and organizations learn. In that such documentation and training can never be complete, the munitions industry should prepare and implement plans for retaining key manufacturing skills for purposes of training, if needed.

Recommendation: The TIME replenishment plans should include agreements to use the human resources departments in the companies with whom they sign dual-use contracts. TIME should carefully review the human resource capabilities of the companies prior to signing contracts and monitor their capabilities as part of periodic readiness reviews. In addition, this information should be included in the capabilities database describing the equipment and process capabilities of the firm.

In anticipation of a national emergency each company that has agreed to make dual-use capabilities available should have the following capabilities in place and ready for implementation on defense manufacturing: (1) up-to-date databases of skills that can be matched against specific government needs under a variety of preselected scenarios, and (2) a method for tying this information to a decision-support tool that enables individual employees and managers to determine, from a host of options, the education or training that can best fit their current skill sets and the replenishment needs at the time of crisis. Management should also have access to a decision-support tool to make rapid, cost-effective decisions about hiring needs, the impact of job transfers, and the need and timing of training programs. Prior to a replenishment need, outside education and training vendors should be able to access the tool to respond, through courseware development, to the anticipated educational and training needs of the organization.

The costs associated with different training scenarios should also be accessible for effective decision making. Given the current and desired skill set and the available retraining mappings from the O*NET database, decision makers should be able to identify optimal or cost-effective alternatives for training and maintaining the skills of the organization's workforce.

The TIME program or large dual-use participants should procure and utilize a decision-support tool satisfying the above needs. Construction of such a tool requires the ability to model the current and desired states of organizational knowledge. A neuro-learning model represented by a data cube could fulfill these requirements. The information could then be used to assist TIME enterprises in organizational learning, thus helping to rapidly transform them from the current to the desired state in the most efficient and cost-effective manner.

Maintenance of Replenishment Manufacturing Capability

For conventional weapons, replenishment capacity for final assembly may not be the most critical issue, since safety and security requirements for these processes result in the U.S. Army maintaining specialized government-owned/government-operated facilities for final assembly. However, manufacturing tasks at lower tiers in the supply chain are more likely to be performed by the dual-use commercial sector. As noted before, the maturing of agile manufacturing is trimming industrial capacities that can potentially meet dual-use requirements.

As a first step in the replenishment analysis process, it is important to quantify the potential requirement on the industrial manufacturing base. A relatively straightforward methodology for the assessment of the risks of an agile manufacturing industrial base can be found in Jones (1995). Implementation of this methodology by the TIME program would likely provide valuable insights for estimating the scope of the problem, as TIME proceeds to begin the process of negotiating dual-use contracts. As Army program managers begin the process, they should verify that the Federal Acquisition Regulations will permit them to negotiate contracts that will enable rapid, cost-effective procurement of munitions when needed for replenishment.

With rapid changes in the U.S. industrial base, TIME must carefully negotiate contracts and regularly monitor the status of equipment and workforces under these dual-use agreements to minimize readiness surprises in the event of national crises. Due to current trends in supply chain integration that are leading to dramatically reduced industrial inventories, agreements for capacities and inventories should be negotiated and monitored several levels down into the supply chain.

As is clear from studies as early as 1996 by the National Defense University and from reviewing the DoD replenishment plan, unless there is an immediate danger to the continental United States, it is likely that future conflicts will not include a concerted industrial mobilization. In other words, most future wars will probably be fought while the U.S. industrial base is operating in a business-as-usual mode, although precontracted dual-use capacity will be called on, if needed, after a second regional conflict. Merely having the ability to transfer manufacturing technology from company to company may be useless if there is insufficient immediate excess capacity in the commercial industrial base or if there are not contractual agreements in place, down the manufacturing supply chain to raw materials, to enable rapid conversion of commercial industrial capacity to military industrial capacity.

Another key issue that the committee believes should be accorded further attention by the TIME program is that of rapidly reconfigurable equipment. This is a topic receiving much attention in the commercial world because of rapidly evolving customer demands and product configurations. It should be a central theme of plans to utilize dual-use commercial equipment for replenishment. In recognition of the importance of this concept for both commercial and defense manufacturing, the National Science Foundation recently funded a center for rapidly reconfigurable equipment at the University of Michigan The committee suggests that the TIME program identify ways in which the munitions industry can avail itself of the capabilities of centers of expertise in reconfigurable equipment.

The Army has yet to begin to take advantage of techniques such as information-based supply chain management, which are used in commercial industry to reduce obsolete inventories and increase the responsiveness of OEMs and suppliers to changing product needs. This is not to say that large munitions stockpiles can be totally eliminated. Rather, it is to suggest some of the huge potential savings that can accrue from a dramatic transformation of the MIB. Labor-intensive munitions production facilities that manufacture relatively simple munitions potentially can be downsized. Emerging needs for flexible, advanced energetics production and storage facilities can be funded in part by closing down obsolete facilities. These new facilities can employ a smaller, more flexible, more highly skilled workforce and can use a wide variety of sophisticated production methods and technologies.

4

Product Realization

"New product realization" is a term that includes the conceptualization, design, testing, production, deployment, and support of new munitions as well as major modifications or enhancements to existing munitions. "Product realization," as defined by the TIME program, is the conversion of customer requirements into delivered products (Burleson 1999b). Currently, as practiced by the Army, this process is lengthy and sequential (Burleson 1999b; Osiecki 1999), resulting in extremely lengthy design-to-production cycles, often exceeding 10 years (McWilliams 1999).

For years manufacturers have dreamed of a computerized, integrated product realization process extending from initial concepts through mechanical design, process planning, costing, production, and beyond. This fully integrated process is beginning to become a reality in commercial industry. Examples include Boeing's development of the 777 and Chrysler's new Jeep Grand Cherokee, which entered production in 2001 and was completed entirely in a digital realm including design, engineering, and factory layout (Banks 1999).

APPROACH TO PRODUCT REALIZATION

Vision

The TIME program plans to implement a product realization strategy based, in part, on that envisioned by the DoE Advanced Design and Production Technologies (ADAPT) Initiative. This integrated product and process development vision includes the following (ADAPT 1999):

- A science-based design capability in which first-principle models and advanced-simulation capabilities form a foundation for the use of advanced tools to support design and optimization. Computer-aided design (CAD) functions are linked with model-based analysis and simulation capabilities to provide the advanced tools needed to understand and optimize product designs and, with computer-aided manufacturing (CAM), enable the production of hardware directly from CAD drawings. This permits the automated design and fabrication of

parts, tooling, fixtures, and gauges with a minimum of unit processing steps.
- Model-based manufacturing approaches, from design validation through full integration and control of the factory floor, that provide the flexibility to respond to changes in product type and demand and to rapidly provide products with zero production defects.
- Selection, validation, and deployment of the tools and technologies needed to support and use advanced computer-aided and automated design and manufacturing systems.
- The ability to readily implement product and process improvements with a minimum of disruption.
- Product qualification and acceptance capabilities that enable on-machine and in-process inspection to eliminate defects in final products.
- Exploitation of the ongoing revolution in information, design, and manufacturing technologies to achieve product realization goals.

The TIME enterprise architecture (Raytheon 2000), described in Chapter 3, captures the vision of the product realization process for the entire enterprise. The architecture facilitates the use of emerging and existing tools to improve product and process integration and to provide a technically sound basis for timely development of robust products, their life-cycle management, and integration with other enterprise systems.

TIME plans to procure commercial off-the-shelf (COTS) technologies, develop those that are not available, and validate and deploy them to create an information-driven, agile manufacturing base. Figure 4–1 illustrates the breadth of tools required to support the product realization process. Integration technologies will be used to facilitate the seamless operation and interaction of these tools to create a virtual distributed enterprise. TIME plans to accomplish many of its goals through a phased set of technology integration, validation, demonstration, and development activities that includes efforts to accomplish the following (Burleson 1999b):

- Generate the initial product realization document with emphasis on mechanical piece parts;
- Update the initial product realization document to include electrical piece parts;
- Evaluate, procure, and integrate initial collaboration tools, including

- The Web Integration Manager (WIM),
- Work flow tools,
- Product and process models,
- Resource management, and
- The design cockpit (see “Conceptual Design Cockpit” later in this chapter); and

- Develop a product realization training program.

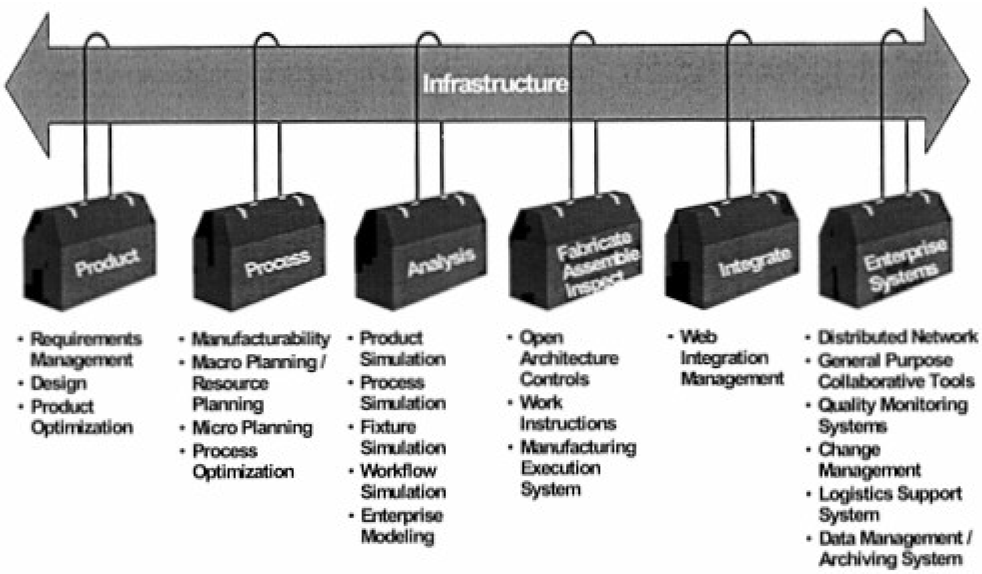

FIGURE 4–1 The range of tools required for integration into the virtual enterprise.

The TIME program addresses the entire product realization process as a system that integrates design, engineering, manufacturing, administration, and logistics. TIME is seeking a systematic approach so broad that even the groups involved in demilitarization of the munitions when they become obsolete will have a role in the design of the munitions. To facilitate the flow of information among various functions, TIME is making use of a host of Internet-based software tools. Many of these tools were developed during the earlier U.S. Department of Energy (DoE) program, Technologies Enabling Agile Manufacturing (TEAM). These Internet-based software tools not only support an open flow of information but also envision modeling of all phases of the work, communication among computing systems for geographically distributed facilities, concurrent engineering and production for teams that may be using different standards, and state-of-the-art methods for controlling manufacturing processes. A WIM pulls together all functions, including product design, process planning, process simulation, and fabrication controls. These integrative elements are what make the TIME approach possible today.

Some of the manufacturing facilities of TIME partners are being used as initial demonstration sites for these integrated models and software tools, demonstrating that Internet-based tools can enable several facilities to work together quickly and easily. These demonstration projects are described in detail in Chapter 6 and in the following case study.

Case Study: Product Realization

Accelerating the new product development process for the munitions industry is a critical objective of the TIME program. According to TIME program participants (McWilliams 1999), the typical time for transitioning a new energetic material to production exceeds a decade. The potential exists for TIME to reduce this time by half by integrating tightly coupled mathematically based modeling and simulation tools throughout the product realization process and by utilizing the TIME enterprise to remotely monitor and troubleshoot production processes. This case study serves as an example of the potential that TIME techniques offer for accelerated product realization.

Background

Current munitions facilities were typically designed and built decades ago for the production of large quantities of munitions in batch operations. In order to provide weapons developers with new energetic materials, which may enable a wider variety of “designer” munitions in smaller quantities, significant changes within the munitions industrial base will have to be realized. Collaboration between DoD, private industry, and academia, for example, can leverage advanced capabilities in modeling and simulation tools to prototype and manufacture the new energetic materials. However, the committee is concerned about security and potential threats to the United States should advanced munitions designs and formulations end up in unfriendly hands.

Under the TIME program a process methodology was developed, key process parameters were computer-captured using sensors mounted on the equipment, and the technology was quickly and successfully transitioned from small-scale research and development quantities to larger-scale production equipment. A communications network was installed, using commercially available technologies, providing a link between industry (Thiokol), government (Picatinny Arsenal), and academia (Stevens Institute) to transfer video and process data real time between sites. In addition to reducing development time, process scale-up errors were reduced and significant improvements in processing safety and reduction in hazardous waste streams were realized.

This program demonstrated two technical accomplishments: (1) the rapid scale-up of a new energetics formulation applying the TIME methodology and, (2) utilization of a TIME-specified network to transfer a process from the laboratory to production scale-up.

The energetic material that was the subject of this case study is an evolutionary, state-of-the-art, high-energy explosive compound for use in shaped charge warheads. The material has been demonstrated to be extremely sensitive during dry handling. The focus of this program was to demonstrate reproducibility in a remote site when scaling up to production quantities. Mathematically based modeling and simulation tools were used to model the crystallization process and determine critical relationships between the physical and chemical characteristics of the material on a microscopic scale and to correlate them to bulk characteristics during processing. The TIME network linked the model to both the bulk laboratory experiments and initial production of the new energetic formulation.

Propellants are currently being manufactured using a large quantity batch method. There has always been variability between batches, much of it caused by the design of the die used to form the final propellant shape. By applying the TIME methodology, a better understanding of the process was achieved and improvements to the existing process were implemented. The instrumented, remotely controlled twin-screw extruder (TSE) increases batch uniformity and operator safety.

Modeling and Simulation Tools

The twin-screw extruder demonstration was conducted at Picatinny Arsenal in cooperation with Thiokol Corporation and the Highly Filled Materials Institute (HFMI) at Stevens Institute of Technology. The project leveraged over 15 years of effort at HFMI in mathematical modeling, 2-D and 3-D finite element analysis, extruder screw design, and experimental validation for extrusion of inert simulants (experimentally "equivalent" energetics) (HMFI undated).

The objective of the modeling and simulation was to determine the effects of extruder process parameters, die designs, and material properties on the uniformity of feedstock mixing. Finite element codes enable the determination of velocity distributions, stress distributions, and temperature profiles experienced by the materials in the extruder and die. By calculating the velocity fields, predictions can be made of the existence of dead zones (i.e., regions where materials may become trapped and agglomerate) (HMFI 1998). Deteriorated materials caught in dead zones occasionally fracture, and the particles can move back into the flow stream and become mixed into the final energetic compound. Deteriorated material can be more sensitive to initiation or it can form defects in the grains leading to performance and safety concerns (HMFI 1998). In addition, energetic materials can be adversely affected by high stress and temperature levels during the mixing and extrusion process.

Accurately modeling and simulating the flow and mixing of energetics through the TSE is quite complex. The models must be validated experimentally over a range of materials, TSE and die geometries, and TSE operating parameters in order to create a sufficiently robust simulation tool. Robust tools can be used to develop new energetic compounds, establish process parameters on different TSE equipment, and transfer processes from the development laboratory through scale-up to full production. In developing such models, the heavy computational requirements of the TSE finite element analysis programs should be carefully considered, due to the fine meshes and short time intervals required to predict flow domains, stress profiles, and temperature distributions along the TSE (Gotsis and Kalyon 1989).

Further details regarding the TSEs are presented in Appendix C and Chapters 5 and 6.

Mechanical Piece Parts

The TIME program has prepared a document called the *TIME Architecture for Product Realization Process of Mechanical Piece Parts* (Raytheon 1999) that serves as their high-level guideline and goals for product realization. The document's purpose is to (1) define an architecture for the TIME product realization process, with an emphasis on mechanical piece parts; (2) identify the elements of the process; (3) define the relationships and workflow among the process elements; and (4) establish the functional and performance requirements necessary to collaborate, share, and manage information from product concepts through manufacturing. This document also outlines aspects of product life-cycle management such as production, deployment, field support, and repair.

The goals of the TIME product realization process for mechanical piece parts are presented below (Raytheon 1999):

- Create an architecture sufficiently flexible to allow the integration of new technologies into the design process without interrupting other processes or resources within the enterprise or the product realization process.
- Establish a process that reduces time-to-market by decreasing rework, reducing the number of prototypes, introducing agile manufacturing techniques, and implementing modeling and simulation software tools.
- Establish requirements for qualifying software tools for integration into the product realization process.
- Create a configuration that allows information, at any stage in the product realization process, to be shared across the TIME network.
- Capture and disperse the design intent early in the product design and development cycle across various groups within the enterprise.
- Establish optional paths between product realization processes so that single point failures are minimized.
- Allow for both synchronous and asynchronous collaboration within the design and development processes.

Product Realization Model

TIME is leveraging the work of the DoE TEAM program to develop an initial product realization environment for mechanical piece parts. The toolset for mechanical piece part product realization is assembled from COTS products integrated with the TEAM-developed and TIME-modified Internet-based software tools. The initial toolset being deployed for mechanical piece parts is shown in

Figure 4–2.[1] Although initially focused on mechanical piece parts, TIME is also pursuing work in electronic assemblies, composites, explosives, and metal forming.

A breakdown of the product realization process shows domain areas of functionality. These areas are called workflow modules, and each one represents specified tasks of the product realization process. The workflow modules identified within the product realization process of mechanical piece parts are as follows (Raytheon 1999):

- CAD,
- CAM,
- Computer-aided engineering (CAE),
- Manufacturing execution, and
- Integrated data management.

TIME intends that these workflow modules be seamlessly integrated for the product to be realized efficiently from concept through manufacturing. To achieve seamless integration across workflow modules, the input, output, and feature requirements must be identified and the methods of interfacing between workflow modules defined. The TIME *Mechanical Piece Parts* document (Raytheon 1999) identifies the high-level requirements of the workflow modules for seamless integration of the product realization process of mechanical piece parts.

The TIME concurrent product realization concept generally 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 should interoperate seamlessly and concurrently to provide accurate assessments of cost, performance, and schedule for conceptual product realization approaches. This seamlessness and concurrency can enable the enterprise and the customer to rapidly evaluate trade-offs of key factors to arrive at an optimized, validated design for the product and its supporting processes.

Studies have shown that implementing a product realization process that utilizes collaboration, concurrency, and agile manufacturing techniques within the business enterprise can save time and money. For example, the DoE TEAM program demonstrated that its model of the product realization process could reduce rework and inefficiencies. TIME will leverage the work done by the TEAM program (Neal 2000) to develop an initial product realization environment for mechanical piece parts. The TIME program's next process discipline focus will be on electronics. This will be followed by die-cast plastic components and then assemblies (McWilliams 1999). Training will also be needed for this product realization environment (ManTech 1999).

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[1] One of the tools shown in Figure 4–2 is the OMAC mill. The committee believes that COTS controllers adequately serve the same purpose as the mill.

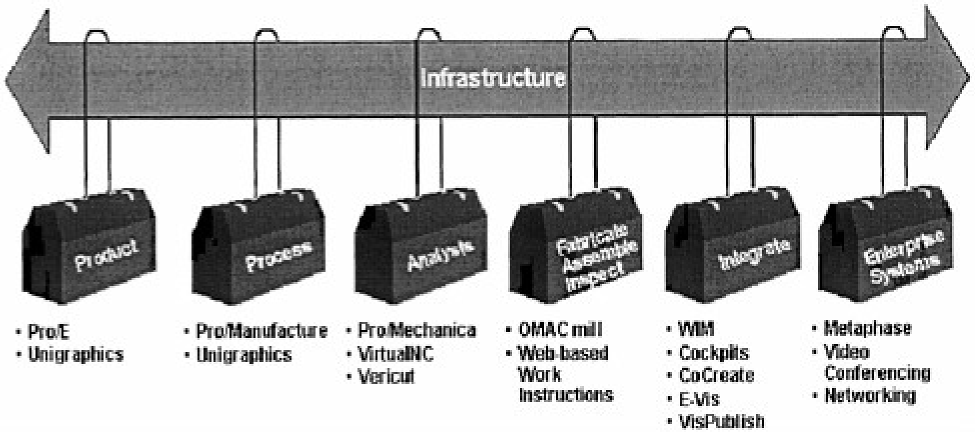

FIGURE 4–2 Initial toolset for mechanical piece part product realization.

Concept Optimization

The generic TIME product realization process (Figure 4–3) is driven by the input of needs (from the customer) and capabilities (from suppliers). During the concept optimization phase, the needs are assessed in the context of enterprise knowledge captured from past experience, including product performance data, manufacturing process capabilities, and munitions enterprise resources.

Concept optimization is the first step. This step will capture the customer requirements and enterprise knowledge for use in developing the product design concepts. Collaboration and concurrency are techniques used to evaluate metrics such as performance, cost, schedule, and risk against the conceptual product design. Balancing the trade-offs early in the product development process eliminates potential rework and determines the worthiness of the project. The output from optimizing the concepts of the product design is a refined set of prioritized requirements, sometimes referred to as a “baseline script,” that feeds into the design optimization phase.

Design Optimization

The design optimization process is based on concurrent development and execution of the “product realization script.” The script is optimized for performance and value by trading off critical parameters in the product, process, and resource domains. All participating stakeholders can access and influence the development of the script. The script is realized during the execution phase, in which acquisition, fabrication, and assembly are conducted to produce deliverable products. Each phase of the process has as its foundation a knowledge base, integrated through an open-architecture infrastructure, that enables team collaboration, interoperability, and portability of tools.

In the design optimization phase, the product design is first constructed into a model from concepts and requirements delivered by the baseline script. The model of the product is used to analyze and optimize the product against its environments throughout the product life cycle. Priorities and trade-offs for a given set of requirements determine the optimal product design. The output of the design optimization step, sometimes referred to as the "manufacturing script," incorporates the product design and information about design for manufacturing.

The design optimization step for mechanical piece parts comprises CAD/CAM/CAE processes. The optimization includes all three elements to ensure that mechanical piece parts can be fabricated within the manufacturing capabilities and will withstand specified operating environments. Special tools such as process simulation are included in design optimization to reduce manufacturing errors, rework, and cost.

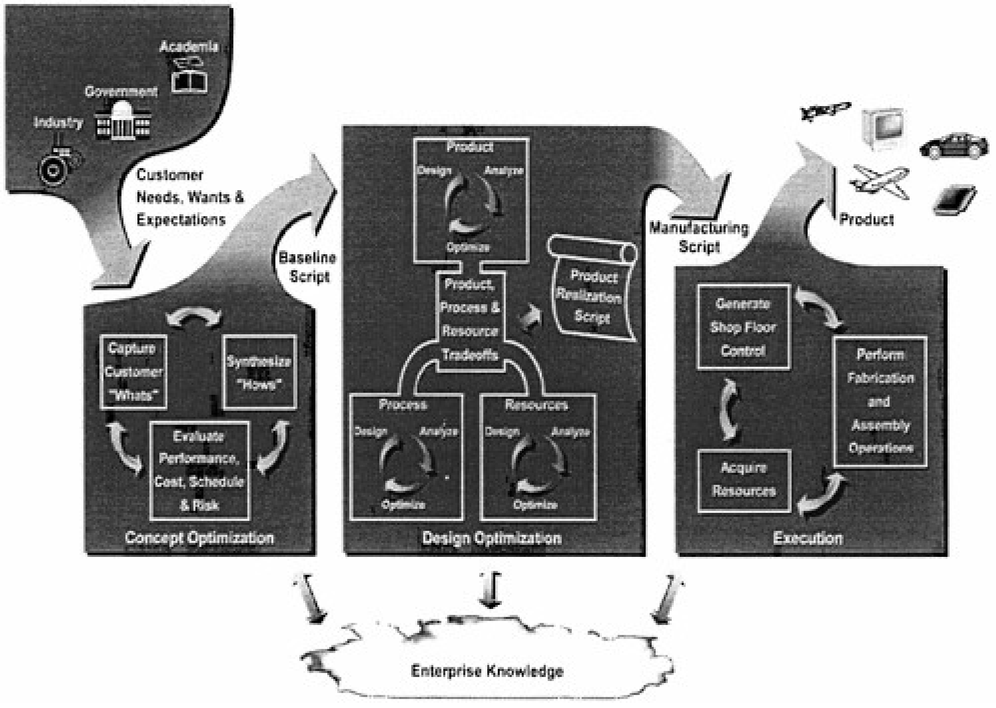

FIGURE 4–3 Product realization model utilized by TIME.

Execution

The execution step includes the manufacturing processes needed for construction of the mechanical piece part based on the optimal design, as presented in the manufacturing script. Execution of mechanical piece parts typically is performed using four processes: (1) material removal, (2) inspections, (3) modification, and (4) testing. The results of the execution step are measures of success for the product realization process. The quality and efficiency of communication and product design are reflected during production, inspection, and testing of the product. Meeting the customer requirements for the new mechanical piece part is the ultimate measure of success for the product realization process.

Conceptual Design Cockpit

Integrated product realization, with its systematic approach to manufacturing, opens the door for knowledge-based systems and automated information generation. TEAM focused its knowledge automation efforts, as a first step, on the concept optimization phase, developing a “cockpit” for conceptual design. This approach is designed to put the customer and other stakeholders “in the driver’s seat.” They make choices about what they want and then quickly and automatically see the results of those choices. For example, the customer might select aluminum instead of steel for a certain part and will then quickly see the resulting changes in weight, structural strength, stress levels, temperature performance, time to manufacture, tolerance capability, and cost (TEAM 1997).

A cockpit is simply an interface to the WIM that enables users to perform some subset of process activities in an automated manner. For example, a conceptual design cockpit allows a single conceptual designer to perform iterative design trade-off studies in real time using the conceptual design tools. Cockpits provide a high level of automation and may also be created for other subsets of the product realization process.

COMMITTEE ASSESSMENT

Computer Aided Design and Manufacturing

Fast and reliable links from concept modeling and simulation to CAD and CAM are fundamental to a modern manufacturing organization. Ideally, the interchange from a concept model or simulation to a design format in CAD to a manufacturing format in CAM and back should preserve all design and process information. In addition, the information should be easy to understand and interpret by participants from all participating functions. Best practices thus include rapid links between design parameters and machine tool commands;

highly tuned, economically operated production equipment; and an appreciation in the design function for fixturing and tooling design. Although as of 1999 less than 15 percent of industrial CAD work had been converted to 3-D (Whitney 1999), modern 3-D CAD environments have been developed to enable high-end solids modeling with real-time rendering while maintaining a parametric model of the emerging design. This means that objects are initially created generically without specific dimensions. When the objects are instantiated (specifically defined in the CAD environment), dimensions are added and the entire design is automatically scaled up or down. Participants in the design process are able to define constraints between different parts of an object and then scale them. These tools are sufficiently powerful for large automobile and aerospace companies. These design environments enable rapid design of similar components in a family. For instance, at a bearing manufacturing company like the Timken Company, design tools are used to design bore sizes, bearing races, and cover plates. Once created, these designs can be easily scaled up or down to create a family of products. Future revisions of a component can be readily created by using existing parametric designs that reside in the software library. They can be quickly reinstantiated to create a new object in the same family.

Constraint-based parametric design has enormous appeal for modernization of the munitions enterprise and the introduction of product variants. However, a substantial investment is needed, not only in technology, but also in training of personnel. There is a significant learning curve for such systems in comparison with less sophisticated drafting packages. Also, since vendors typically issue new revisions of parametric systems approximately every 18 months, ongoing investments in system upgrades and user retraining will likely be required.

These COTS parametric systems also have direct links to supplementary packages that will do design for manufacturing and assembly (DFM/A), design for environment, and finite-element analysis. Most of them also include a Common Object Request Broker Architecture (CORBA) based on open architecture that allows linking to other software applications. Commercial CAD products in this category include the following:[2]

- *ProEngineer*. Commercially available online from <www.ptc.com>,
- *IDEAS*. Commercially available online from <www.sdrc.com>,
- *Unigraphics*. Commercially available online from <www.ugs.com>,
- *CATIA*. Commercially available online from <www.catia.com>.

Translations between different commercial CAD systems, traditionally a major problem, are becoming less difficult. Translations once done with the Initial Graphics Exchange System can now be performed using the Product Data Exchange System/Standard for the Exchange of Product Model Data (PDES/STEP). (The acronym PDES is also used for Product Data Exchange

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[2] Although the committee strongly recommends that the munitions industry begin using integrated COTS CAD/CAM systems of the types presented in this list, the list is by no means complete and does not constitute an endorsement of any specific commercial system.

Using STEP.) Although experience shows that some glitches (or errors) can still occur during translations between systems, PDES/STEP is evolving into a useful commercial worldwide standard. While one option would be for the entire munitions industry to use CAD tools from the same vendor, this is neither practical nor desirable. Thus, TIME should focus a substantial portion of its CAD-related efforts on detailed definitions of user needs for design systems, monitoring the evolving graphics exchange standards, and ensuring that the munitions enterprise system will remain operational and as error free as possible, as the exchange standards, hardware, and software systems used by the various participants migrate.

Recommendation: The TIME program should focus a substantial portion of its CAD-related efforts on detailed definition of user needs for design systems and should not invest TIME funds in developing graphics exchange standards.

How can a team effectively design for manufacturing when it is impossible to know all of the evolving equipment, processes, facilities, controls, materials variations, and manufacturing conditions that may be encountered in trying to produce a munition over the decades during which it may be produced? Because it is not possible to know or anticipate all of these manufacturing characteristics, it is important that TIME select and implement systems that can assist the engineers over the life of the product. Thus, it is important that the munitions industry adopt an environment that supports downstream manufacturing and surrounds the diversity of CAD systems used in the industry. Examples of such environments include ProManufacture and System Dynamics Research Corporation's (SDRC's) manufacturing shell.[3] Within these environments, skilled set-up engineers carry out process planning and generate downloadable machine code. During this important step of process planning, CAD features can be mapped into physical features that are eventually machined into a piece of material using a computer numerical control (CMC) machine tool.

Process planning is the important bridge from CAD to CAM. It involves seven steps:

1. Recognize the features that the designer created.
2. Analyze how the features overlap and intersect.
3. Map the geometry of these features to the capabilities and geometries of the downstream manufacturing machines.
4. Select appropriate fixtures and associated set-up routines for processing.
5. Specify the running parameters of the machinery.
6. Detail the in-process and postprocess inspection routines.
7. Provide a quality assurance report that ties together all of the information related to the part.

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[3] Examples should not be interpreted as a committee endorsement of a specific commercial product.

Once process planning is complete, specific programs are sent to the machine tools. For example, the detailed movements of standard machine tools are controlled by “G” and “M” codes, which were developed in the 1950s and are extensively used in commercial industry today. Even though these methods have been automated, they still form the communication routines for most of the low-level loops in today’s CMC machines. G and M codes have also been integrated into the RS-274 standard (Electronics Industries Association 1979). Automatically Programmed Tool (APT) is a higher-level language that enhanced the G and M codes and treats each line in a CAD figure as an object. Methods based on APT are still used for machine tool programming in today’s factories. However, other high-level programming tools that automatically break down CAD features into individual tool paths are also available. Without these higher-level programming environments, all of the machining process details, such as tool-offsets and ordering of the roughing and finishing cuts must be specified by the process engineer.

In summary, among the most important and beneficial actions of TIME should be the selection and implementation (where none exist) of appropriate CAD/CAM systems and manufacturing environments for process planning and machine tool programming. TIME should also focus on issues of interactivity and interoperability between myriad CAD/CAM systems used in the munitions and dual-use industries and on ongoing commercial efforts to improve interoperability of COTS systems such as PDES/STEP, as well as their integration with the broader manufacturing environments for process planning and machine tool programming. These COTS CAD/CAM systems and manufacturing environments are being used on a daily basis by a myriad of large corporations and thousands of small machine shops across the nation.

The committee believes that TIME should systematically analyze the CAD/CAM needs of the munitions industry, select the implementation opportunities that offer the largest stand-alone return on investment (ROI), and begin to procure and install appropriate, up-to-date COTS systems. Rather than continuing to focus on connectivity and interoperability issues, the emphasis should be on selection, installation, debugging, and operator training. Later, as commercial efforts improve the performance of PDES/STEP translation systems, the ROI will also improve, such that the use of scarce funds on such interoperability enhancing systems can be justified.

If it is to integrate with commercial industry for replenishment, the munitions industry must stay current with the evolution of tools used for commercial design and transition to production. TIME can serve a valuable function in this regard by monitoring and evaluating new tools and developing means to seamlessly integrate them into the munitions industry. In this regard, the committee recommends that TIME pay particular attention to new concepts for “design to manufacturing” that may someday replace CAD/CAM.

Modeling and Simulation

Rapidly changing world events place increasing pressure on defense programs to reduce the time required for product realization. Defense programs are increasingly recognizing the powerful increases in productivity and significant decreases in cost enabled by modeling and simulation. The Army, for example, has recognized that modeling and simulation are emerging as key technologies for product realization in the 21st century. At Aberdeen Proving Ground, Maryland, modeling and simulation tools, enabled by high-performance computer capabilities, are being used to design and test concepts for advanced munitions. Huge benefits accrue from weapons simulation because munitions testing is inherently expensive and hazardous. The armed services are also using modeling and simulation in the design and evaluation of advanced energetic materials—systems that are likely to play a key role in munitions of the future because they will require (McWilliams 2000a):

- Higher energy,
- Lower sensitivity,
- Better quality,
- Smaller quantities,
- Shorter lead times, and
- Lower cost.

Unfortunately, according to McWilliams (2000a), the Army has yet to implement CAD and CAM systems that are interoperable with their modeling and simulation capabilities. Thus, as munitions concepts mature, information must be downloaded and re-entered into CAD/CAM before physical hardware can be produced. Although not currently a part of TIME program plans, this is but one example of the near-term opportunities to implement some of the key technologies outlined in the TIME enterprise architecture and to enable a substantial return to the taxpayer.

Finding: DoD is increasingly using advanced modeling and simulation (M&S) techniques, enabled by high-performance computing, to create and test advanced energetic materials and advanced munitions. However, the government-run munitions facilities have almost no CAD/CAM and manufacturing environment tools, the implementation and interconnection of which to M&S would result in huge savings in cost and schedule.

Finding: Given its relatively neglected state, Army munitions design and production operations would benefit substantially from the rapid implementation of stand-alone COTS CAD/CAM systems.

Recommendation: The Army should immediately begin to implement COTS CAD/CAM/CAE systems in the munitions industry. Interoperability between these systems is an issue of secondary priority.

Importance of First Prototype

Even the smallest design changes can be disruptive to production. Modifications to manufacturing records, instructions, and machine programs must be made, sometimes corrected, and eventually proven good. Numerous decisions must be made, such as whether old style parts can practically be finished, reworked, or scrapped or whether unmachined blanks can cost-effectively be machined into new style parts. The TIME program aims to accelerate the process of transitioning new and modified designs into production, reduce the amount of errors and scrap during transition, and reduce the number of changes by doing things correctly the first time.

Online collaborative product realization is a cornerstone of the TIME program. The connectivity of computer programs proposed by TIME could allow quick and easy engineering analysis of new designs and result in a higher percentage of correct first prototypes and fewer design changes during production. Manufacturing is likely to become more computerized in the future, and generative process planning, in which information is passed directly between the product design computers and the manufacturing engineering computers, may be able to reduce the number of false starts of the manufacturing process and provide consistent methods to the shop floor. New machine programs will likely be produced by computers that utilize information passed to them by process planning software. It is likely that these programs will be simulated, checked, and downloaded to the CNCs that control the machines.

Realization

Virtually all commercial manufacturing organizations are now aware of the need for rapid response to changing markets, agile production, and fast development of new products. Regardless of the product, the technologies and business practices that support the development activity are critical. Assisted by human resource departments, innovative commercial manufacturing organizations now strive to develop group problem-solving strategies. There also has been a trend to use business process re-engineering and to shed unnecessary layers of middle management.

Multidisciplinary Design

The next frontier in product design may focus on efforts to integrate the multiple design technologies required to create complex systems. Systems typically consist of both mechanical and electrical subsystems, blended and integrated into an interoperable mechanism. For example, designing and fabricating new, complex munitions that include electromechanical systems requires collaboration among multiple engineering disciplines. In spite of the advancements within each field, a communications/interoperability gap still exists between electrical computer-aided design (ECAD) and mechanical computer-aided design (MCAD) systems. Environments such as SDRC's Metaphase[4] have been developed to address this need. Metaphase is a concurrent engineering system for ECAD/ MCAD. The links from conceptual design, to detail design, to fabrication are smooth and deterministic, creating a fast link from an initial design to a fabricated product. This integration improves both product quality and time-to-inventory. With emphasis on constraint resolution between electrical and mechanical issues, Metaphase creates a central, virtual white-board environment that can share and communicate coupled design issues during the design process. In the longer term, TIME should investigate systems such as Windchill, Metaphase, and Matrix-1, as well as Internet-based products.[5]

Recommendation: The TIME program should investigate and implement COTS software packages that enable more effective communication among a variety of CAD and CAM systems.

Rapid Prototyping

Since the introduction of practical rapid prototyping processes approximately 20 years ago, these technologies have become an important part of rapid, cost-effective product realization processes in many industries. The combination of CAD/CAM with rapid prototyping technologies can accelerate time-to-inventory by improving the design/manufacturing/customer interface. Recently developed CAD tools can be electronically linked to rapid prototyping tools and full production. For example, tessellated CAD models can be linked to the rastering movements of a laser beam in a stereolithography process, to sinter lasers for fused deposition, or to other solid free-form fabrication processes to rapidly create mechanical prototypes. Many participants in the munitions industry cannot justify ownership of their own rapid prototyping capabilities. However, commercial rapid prototyping capabilities are readily available and should be used as needed. Design files can be sent via e-mail, and finished prototypes can typically be delivered in 1 to 2 days via overnight delivery services.

Recommendation: The TIME program should maintain a thorough understanding of developments in the field of rapid prototyping technologies and links from CAD to prototyping to CAM. The munitions industry, however, should typically avail itself of commercial rapid prototyping services.

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[4] Not an endorsement

[5] Not an endorsement.

Knowledge, Expertise, and Reasoning

The TIME program faces substantial challenges in attempting to capture design knowledge so that it can be readily accessed from future designs. A significant portion of a designer's expertise comes from experience, much of which is difficult to capture and convert into a useful database format. However, due to declining funds, an aging cadre of experienced munitions designers, and infrequent programs to redesign or invent new munitions, much of this expertise is disappearing.

An organization's knowledge capital resides with the people in the organization. For technology transfer to be successful, their skills and knowledge must be captured, preferably using computerized methods for knowledge capture and dissemination. In addition to the finite-element-analysis methods used in commercial design and manufacturing, expert systems (Barr and Feigenbaum 1981) are valuable for formulating solutions to manufacturing problems that cannot be solved using quantitative analysis. Since the early 1980s, expert systems have been useful in solving a wide variety of scheduling problems (Adiga 1993). Expertise is gathered by a formal questioning and recording process known as knowledge engineering. In this approach, engineers work with factory-floor personnel to compile records, tape recordings, and videotapes. These are assembled into a qualitative model of the approaches needed for problem solving. In situations where manufacturing data are more quantitative, conventional relational databases or object-oriented databases are more useful (Kamath et. al. 1995). At a high level, such databases can be used to describe the corporate or program history in terms of typical products, batch sizes, and general capabilities. At a medium level of abstraction, specific capabilities of factory-floor machinery might be described, including achievable tolerances, operational costs, and availability. At the lowest level, databases might contain, for example, carefully documented procedures for lithography and etching times. In any industry, the immediate availability of accurate manufacturing parameters for machinery setup and diagnosis is quite valuable. Such databases also facilitate incorporation of DFM/A data structures.

Realization Speed

Two fundamental technological changes, enabled by the World Wide Web, are distributed computing and client-side, or browser-side, processing. These applications are expanding the capabilities of distributed design, planning, and fabrication environments. Direct business-to-business transactions that minimize transaction costs are improving the speed and efficiency of supply chains. Curry and Kenney (1999) describe these new approaches in their recent article "Beating the Clock: Corporate Responses to Rapid Changes in the PC Industry." A recent article in Forbes magazine "Warehouses That Fly" succinctly captures the speed of production in the microcomputer industry. It emphasizes that the old idea that inventory is kept in a big warehouse is dead. Inventory levels in many industries have been dramatically reduced, and a significant amount of remaining inventories are actually in transit via FedEx or DHL cargo planes or being sorted at the airport hub for next day delivery (Tanzer 1999).

Economic pressures, particularly related to the quality of manufactured goods and time-to-market, are forcing designers to think not only in terms of product design but also in terms of integrated product and process design and, finally, in terms of deterministic manufacturing planning and control. These needs are correctly driving TIME's vision of eventually connecting today's urgent need for low-level integration tools (CAD/CAM and the like) to the extended enterprise. In this fully developed enterprise, there is a great need for comprehensive models that predict material and chemical behavior during manufacturing processes, the pressures and temperatures associated with chemical products, and the final product integrity. Some of this work is beginning at Aberdeen Proving Ground with the high-performance modeling and simulation of new munitions designs. It is concurrently getting under way as part of the TIME program's efforts at Picatinny Arsenal, Stevens Institute of Technology, and Thiokol Corporation to model and electronically control advanced twin-screw-extruder processes for processing energetics. These efforts are representative of the advancements required to modernize the munitions industry. The overall goal is a rich CAD/CAM environment with physically accurate finite-element-analysis visualizations of the manufacturing process and access to process planning modules that allow detailed life-cycle cost estimates.

Economically, the aims are to ensure a high-quality product and to reduce time-to-inventory by eliminating ambiguities and rework during CAM (Richmond 1995). For example (Halpern 1998), Grundig states that the dies for their front and back television casings cost approximately $300,000 each. A single change to one of these dies typically costs $30,000, or 10 percent of the original die cost. Integrated CAD/CAM systems are important tools for minimizing such rework during mold design, fabrication, and try-out. Computer-integrated manufacturing systems are flexible, reconfigurable production systems that can further help an organization to operate profitably even with frequent changes in production volumes and product design. These are topics that TIME should investigate, analyze, plan for, and implement as appropriate.

5

Controllers

INTRODUCTION

This chapter defines basic terminology and control concepts and then describes the control needs of the munitions industry, as expressed by participants in the Totally Integrated Munitions Enterprise (TIME) program. It then explains the capabilities and limitations of todays commercial off-the-shelf (COTS) controllers, followed by an account of the ongoing efforts to develop a truly open control architecture and interchangeable components. The last section presents the committee's assessment of control needs for the munitions industry.

An assessment of machine control technologies should begin with a list of the production equipment and processes to be controlled. The manufacturing operations conducted in the munitions industry fall into four broad categories: (1) fabrication of metal and plastic parts, (2) assembly of electrical components, (3) energetics processing, and (4) final pack and load. A list of parts fabrication equipment at the Downey Operations facility of Primex Technologies, a prime munitions contractor, although more up-to-date than government-operated facilities, is perhaps typical (Cary 2000):

- High-volume turning

- Multispindle lathes,
- Multispindle Davenport screw machines, and
- Multispindle automatic chuckers,

- Computer numerical control (CMC) machining

- CMC lathes,
- CMC chuckers, and
- Multiaxis machining centers,

- Precision grinding,
- Wave solder,
- Plastic insert molding,
- Automated finishing,
- Painting, and
- Inspection and testing.

Appendix C presents operating details and controller requirements for a typical "melt pour" method for processing energetics, as well as another method, the twin-screw extruder. This information was assembled by the TIME program in

May 2000. The only other specific set of machine control requirements for the munitions industry of which the committee is aware is the *DOE/OMAC Department of Energy Open Modular Architecture Controller Milling Machine Requirements* issued in January 1999 (LLNL 1999). The committee believes, based on presentations by the TIME program, that these applications are representative of the most difficult applications in the munitions industry. Much of the equipment in government-owned/government-operated (GOGO) munitions facilities was installed before the era of electronic controls, with few upgrades since.

Control of these types of equipment has traditionally been performed by either CMC or programmable logic control (PLC). It is not unusual for manufacturers to have tens or hundreds of numerically controlled machine tools in a production facility, each with its own proprietary controller. Due to the proprietary content of early controllers, each piece of equipment was an “island of automation,” impossible or difficult to connect to other equipment or to manufacturing information systems. By 1986, control engineers were able to successfully connect together machine tools, measuring machines, wire-guided vehicles, computers, tool gauges, and materials requirements planning (MRP or MRP I) systems, each from a different manufacturer. These pieces of equipment provided manufacturing equipment with basic motion and device control capabilities but typically provided the user with minimal configuration options and had limited communication capabilities.

More modern controls that are used to run these pieces of equipment, such as those encountered in modern dual-use or commercial munitions facilities or those that would be used to upgrade government-owned facilities, typically consist of a collection of interconnected software and hardware modules but with more ability to configure the system and more openness in terms of communications capabilities. These modules contain software that implements two different kinds of interfaces. Functional interfaces between the software modules are called application programming interfaces (APIs). Component interfaces used with the APIs allow system integrators to choose modules with the functionality required for the specific application, connect the chosen modules together, and verify that all required system components have been properly connected. Until the last 3 to 4 years, nearly all machine tools were equipped with proprietary real-time controllers with specialized human-machine interfaces (HMIs). Recently, the major suppliers of CMC controllers have provided access to expanded functions of the controllers through general-purpose microcomputer front ends. In addition, proprietary controller manufacturers have been challenged by suppliers of CNCs using microcomputers with real-time extensions to the operating system.

INDUSTRIAL NEEDS AND DESIRES

At the beginning of the 21st century, the needs and desires of the munitions industry are similar to the needs and desires of much of commercial industry. For instance, TIME believes that numeric control using the Standard for the Exchange of Product Model Data (STEP), called STEP-NC, could increase the productivity of integrated supply chains in a wide variety of industries. TIME also believes that if industry starts using STEP-NC in a major way, it would be desirable, though not essential, that the munitions industry move to adopt STEP-NC to enable more rapid, cost-effective supply chain integration, especially for purposes of replenishment.

Both commercial and defense manufacturing operations would benefit from the ability to provide incremental upgrades, which is a way to increase the useful life of controllers. Further, the ability to add modules would allow the munitions industry to build safety systems into the controls or add them later, as needed. The capability to do model-based manufacturing will potentially benefit most types of industries.

COMMERCIAL OFF-THE-SHELF CONTROLLERS

Today's COTS products from companies like Siemens, Modicon, and Rockwell Automation are characterized by three basic similarities: (1) division of PLC logic and complex motion, (2) difficult integration between vendors, and (3) use of the Distributed Component Object Model (DCOM) as an integration standard.

DCOM is the de facto standard for communications integration between controller components. As such, it must be examined against the needs, desires, and constraints of the munitions industry. DCOM was designed for desktop equipment. Real time in the desktop world is measured in terms of seconds. DCOM has been heavily leveraged by HMI users to provide easy integration for commercial controllers. The effort associated with object linking and embedding for process control within the controls community has shown the power of the DCOM technology when applied to realistic control problems.

The implementation of DCOM still provides challenges to the controls engineer: (1) difficult domain-to-domain integration, (2) possible large-packet-delivery latencies, and (3) large timeouts due to packet failure. Each of these areas is examined below.

Difficult Domain-to-Domain Integration

DCOM requires that users meet all security requirements on the server machine before they can access it. This means the user must have an account with identical privileges on both the client and server machines. This model works well within a particular network domain but is difficult to configure across domains. In the normal solution, the user is configured as an administrator across both machines, which violates security policies designed to protect the system. This configuration is difficult within a single vendor's product family, let alone between two different vendors. Domain-to-domain DCOM integration difficulties have, to date, prevented true enterprise-wide integration of control information.

Large-Packet Delivery Latencies

Many machinery and process control applications require near real-time response. Communication delays can result in safety hazards or ruined product. DCOM communications are normally transmitted on a company's ethernet infrastructure. Data loading on the corporate network is highly unpredictable. DCOM's use in real-time situations requires deterministic bounded response, which is impossible to guarantee when it must compete with unpredictable amounts of additional traffic. There are products, such as high-speed switches, that can help to alleviate possible large-packet delivery latency problems, but they cannot reliably solve the problem throughout an enterprise that may span the globe.

Large Timeouts Due to Packet Failure

Because DCOM was built on top of object-linking-and-embedding technologies from Microsoft, one of its basic legacy issues is that timeouts of up to several minutes can be caused by a packet failure. A client or server may not be notified of a delivery failure for up to 6 minutes. This characteristic is a major impediment to the adoption of DCOM for critical roles.

The DCOM standard has led to major revolutions within the HMI and supervisory-control-and-data-acquisition industries. However, DCOM's adoption for applications that demand real-time response is limited by its configuration and by the possibility of large-packet latencies and long timeouts.

EFFORTS TO DEVELOP OPEN MODULAR ARCHITECTURE CONTROLLERS

Concept of Open Architecture

There are many interpretations of the word "open" in the machine tool industry. Most controllers sold today are open at some level, but no currently available controller is open at every level. When a control uses some type of standard interface, it can be considered open within the context of that interface in that any software or hardware object that adheres to the standard may be used. Open software generally means a standard library to which everyone has free access. Open hardware generally includes a published input and output schematic diagram that enables anyone to interface to the product. Because open architecture controllers typically consist of both hardware and software, a completely open product offering must contain both open hardware and software.

The microcomputer is an example of a highly successful open architecture system. Users can choose from a wide selection of plug-and-play hardware components, such as keyboards, video monitors, and sound cards. A massive number of software products are available from a wide variety of sources. Although these products interact and operate almost seamlessly within the open architecture framework, hardware and software suppliers are able to retain levels of proprietary technology sufficient to enable a high degree of profitability without impeding interactivity. By eliminating barriers to interconnectivity and interactivity, the microcomputer's open architecture has enabled huge benefits and cost savings that may never have accrued with more restrictive or closed architectures. Proponents of open architecture controllers believe that similar benefits will accrue from the development and universal adoption of a similar open approach to machine control.

History of Open Architecture[1]

When a few machine tool users and researchers began requesting open architecture controllers in the early 1990s, machine tool builders typically tried to satisfy these demands with microcomputer-based systems. Although they used a general-purpose computing platform, these controllers were no more open than their predecessors. Users remained locked into the original supplier for hardware and software upgrades and functionality improvements, just as most of today's microcomputer users are locked into Microsoft Windows.

It wasn't that machine tool builders did not want to satisfy the customer. Rather, the demand was extremely small and was predicted to remain small. They also had an overriding concern that by enabling customer access to the controller they would create the possibility of customer error, and the cost of adding the hardware necessary to make a software real-time control loop competitively fast would have significantly increased the cost of the CMC. They feared that inexperienced customers would make programming changes that could cause serious problems and expose machine tool builders to liability lawsuits.

"Flexible architecture" controllers available today satisfy most user needs, in that they permit interoperable and interchangeable product selection. They have a clearly defined input and output model at desirable component levels. However, they also require at least one proprietary hardware or software component to function. A high percentage of users do not care about this, but a concern of Open Modular Architecture Controller (OMAC) advocates is that if the manufacturer decides not to support, maintain, or supply the proprietary element of the system, the system could be rendered useless. This concern is especially compelling in U.S. defense manufacturing industries because these proprietary elements are available only from non-U.S. sources.

Many motion control card suppliers provide a basic numerical control (NC) front end that they call "open." It is called open because the interface definitions are provided, so that the user or third-party integrator has full access to the controller's functionality. In a research environment or in the development of specialty machines, this is a good option. However, this interface definition is only for a specific, limited set of hardware. For example, according to Robert Hillaire of the University of California, Berkeley (Hillaire 2000), OpenCNC from

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[1] A more detailed history is presented in Appendix B.

MDSI (Ann Arbor, Michigan) satisfies many of the requirements for openness. It has a front-end application programming API that provides access to important process information. However, while it allows the use of a variety of third-party hardware options, OpenCNC does not provide a truly open interface to third-party hardware. Although it provides more choice than typically available, the selection of hardware is still restricted. Only if MDSI provided an API or hardware-drive standard for the system that allowed all hardware manufacturers to develop products that fit the standard, would OpenCNC be a truly open architecture system. Further, to be truly open, MDSI must modularize its software and provide an API for communication between modules.

International Efforts

Efforts to develop a truly open architecture began in Europe in 1992 with the Open System Architecture for Controls within Automation Systems program. Japan began work in 1994 on the Open System Environment for Controller program.

Department of Energy Involvement in OMAC

The U.S. Department of Energy (DoE) has often encountered unique problems with controllers. On multiple occasions when designing a new custom machine, Lawrence Livermore National Laboratories (LLNL) has encountered a need to design a new controller. The large optics diamond turning machine (LODTM) is a good example. This machine was designed in 1980 to manufacture the resonator optics for the Air Force's Space-Based Laser. These were 1.5-meter-diameter optics with surfaces accurate to 0.1 micron. When designing LODTM, LLNL wanted to use a commercial controller but ran into problems. The turning machine has only two axes but uses seven laser interferometers and six capacitance gauges to measure positions on the two axes. Hence, a complex calculation is required at an update rate of 1 millisecond. LLNL sent a request for quotations (RFQ) to commercial CNC manufacturers and received no responses. They were told that the CNC manufacturers would be better off investing their available resources on other, more profitable projects, even if LLNL offered to pay for development. Similar examples could be cited for other DoE facilities.

In 1994 the General Motors Powertrain Group (GMPTG) came to LLNL with their *Requirements of Open, Modular Architecture Controllers for Applications in the Automotive Industry* white paper (OMACUG 1994). LLNL recognized the similarity of its needs. If the automotive companies could drive these concepts into general availability by including them in their RFQs, LLNL would have a commercially available source of reusable, component-based controllers and could exit the custom controller business.

With these objectives in mind, LLNL drafted a Cooperative Research and Development Agreement in 1994, which said, in part (Rosenberg et al., undated):

> The goal of an open architecture controller is to create an environment, which allows the largest variety of control problems to be solved over a wide range of performance and price. It is NOT to create a single controller, which will be able to solve every possible problem. Rather it is to create a controller architecture, which is sufficiently flexible and scalable, so the reasonable tradeoffs between performance, price, and flexibility may be made by the end user.
>
> If this environment is properly designed, it should allow an end user to solve virtually any real-time control problem (within the constraints of hardware performance and cost). In other words, it would allow end users to create a multitude of controller solutions based on a standard environment, paying for extra performance only where needed.

These high-level goals remain unchanged today.

The goals of OMAC are as follows (OMACUG 1994):

- *Open*. Allowing the integration of off-the-shelf hardware and software components in a de facto standard environment;
- *Modular*. Permitting plug-and-play of components;
- *Scaleable*. Enabling easy and efficient reconfiguration to meet specific needs ranging from high end to low end;
- *Economical*. Achieving low life-cycle cost; and
- *Maintainable*. Supporting robust factory floor operation (maximum uptime), expeditious repair (minimal downtime), and easy maintenance.

In an effort to promote the vision of open control architecture, LLNL teamed with GMPTG and others to develop a set of APIs for an open architecture controller. These APIs (OMACUG 1999) define the environment for solving control problems. Work was begun in 1995 under the auspices of the DoE TEAM program. In a further effort to promote these open architecture control solutions, the OMAC Users Group (OMACUG) was formed in 1997 by the automotive companies and approximately 10 other large end-users. This group has grown to over 200 participants, including Allen-Bradley, Boeing, Bosh, Caterpillar, Cummins Engine, Daimler Chrysler, Deere, Delta Tau, Eastman Kodak, Ford, GE Fanuc, General Dynamics, General Mills, General Motors, Goodyear, Indramat, Ingersoll, Makino, Mazak, MDSI, Microsoft, Monarch, Okuma, Pratt & Whitney, Siemens, and STEP Tools.

Approach to the Needs of Commercial and Munitions Industries

In 1996, the General Motors Powertrain Group Manufacturing Engineering Controls Council authored a paper titled *Open, Modular Architecture Controls at GM Powertrain* (Taylor et al. 1996). This document presented three key strategies discussed in the sections that follow.

Math-Based Manufacturing

The first strategy involves the use of math-based manufacturing. Following is an excerpt from the GMPTG document (Taylor et al. 1996, p. 10):

> Math-based manufacturing is one of the key manufacturing strategies at GMPTG. The goal of this strategy is to link mathematical models of product design, casting design, and machining design into a single three-dimensional math model for a particular product such that the math model can be used in the manufacturing processes directly in electronic form. If changes are made in the product design process, appropriate changes in the casting model and machining model will be made automatically to accommodate the product changes.
>
> It is necessary to have an agile manufacturing system to support the math-based manufacturing strategy because the manufacturing processes need to be able to take a 3D math model directly and produce the products efficiently. The manufacturing systems also need to be agile to handle the frequent changes in product design. The common control platform at each machine allows a common networking approach for downloading of math data, thus OMAC technologies become one of the key enablers for the successful execution of the math-based manufacturing strategy.

GM’s term “math-based manufacturing” is a combination of the precepts of agile manufacturing, integrated product and process development, concurrent engineering, art to part, and many other modern manufacturing concepts. Math-based manufacturing is a major strategy of the TIME program. The part of this strategy that applies to the OMAC is the concept of driving the mathematical model down to the shop floor, commonly referred to as “art to part.” The ability to drive the mathematical model directly from computer-aided design (CAD) to the shop floor offers estimated process planning and manufacturing control savings of between 35 percent and 75 percent (Burleson 2000). It also has supply chain implications. Traditionally, suppliers took the model provided by the prime contractor and separately developed the information needed to drive their process equipment. This requires manipulating the data for each type of process equipment and each type of control. In going directly from art to part, the supplier would use the identical database to manufacture the product that the prime contractor used to design the product, thereby eliminating some of the intermediate work. This not only saves time and cost but also eliminates several potential sources for error.

The OMAC is planning to use the emerging STEP-NC standard as a replacement for the Initial Graphics Exchange Specification. STEP is being designed to address both process information and product information. To that end, an international committee is using STEP to define NC data as a replacement for RS-274. True art-to-part capability has been demonstrated and the controllers are now designed to accept feature-driven STEP-NC information directly.[2] To this end, the National Institute of Standards and Technology has funded an advanced technology program to STEP Tools, Inc., titled *Model Driven Intelligent Control of Manufacturing* available online at <http://www.atp.nist.gov/www/comps/briefs/99014035.htm> with the goal of putting together the toolset required to create STEP-NC data from a standard STEP database and using that to drive controllers on the shop floor. Simultaneously the TIME program is modifying the architecture of the OMAC to accept STEP-NC information directly, without any translations. In this effort, General Dynamics Land Systems will deploy a controller on a Bridgeport mill at the Scranton Army Ammunition Plant (Albert 2000). This approach is intended to benefit commercial industry, DoE, and the Army.

Reduction of Control System Development and Integration Time

The second strategy is intended to allow for the rapid changeover of manufacturing systems from one product to another. Following is another excerpt from the GMPTG document (Taylor et al. 1996, p. 12):

> With the pressure on GMPTG manufacturing systems to adjust to the fast changing demands from the marketplace, the time required to design and integrate a control system needs to be greatly improved in the near future. When OMAC-based control systems become more prevalent, most control components will conform to the standard interfaces and become interchangeable (plug and play). Software tools will also be more available to assist control engineers to perform the system integration tasks. The need to train and re-train personnel will be reduced, further reducing the system integration time.

One example of a rapid changeover requirement cited by TIME sponsors was a GM example of the need to change a transfer line that makes the 2.8L cylinder heads to one that makes the 4.3L cylinder heads. In the early 1990s. GM

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[2] This capability was demonstrated in July 2001. The prepublication document postulated this development.

was selling as many S-10 trucks as it could make 4.3L engines. The problem was that the company had invested heavily in the 2.8L engine and had installed transfer lines to build it. Hence, it had excess production capacity for a product that few people wanted and insufficient capacity for the product that people wanted. The production changeover to the new engine required 18 months, an unacceptable amount of time in an era of rapidly changing consumer demands. GM wants to reduce that time on this and other production lines and, according to the TIME program, sees the OMAC as a necessary enabling technology (Burleson 2000).

The committee, however, does not believe that this is a valid argument for the OMAC. In the 1970s and 1980s, U.S. CMC makers urged the American auto makers to begin using NC machines to reduce changeover time and cost. They resisted while their Japanese and German competitors went ahead and tried them. The non-U.S. auto makers proved in practice during the 1980s that these benefits were readily achievable with 1980s model CNCs. OMAC technology was not necessary. Even today only a small percentage of U.S. auto parts are made on CMC equipment.

The TIME program believes that the situation in the munitions industry is similar to that in the U.S. auto industry. The Army wants to be able to rapidly change equipment from commercial production to munitions production if needed to replenish its stockpile. For companies like GM, to change from building a commercial product to building munitions requires a lengthy changeover of equipment. TIME program participants see the OMAC as a means to help them achieve that goal just as GM sees it as a means to help it achieve its engine manufacturing goal. This doesn't mean that such changeovers cannot be accomplished without the OMAC, just that it is somewhat easier and probably much quicker with the OMAC's modular technology (McWilliams 2000b).

Incremental Upgrades of Control Systems

A third strategy allows easy upgrade paths. Following is a third excerpt from the GMPTG document (Taylor et al. 1996, p. 12):

> When functional add-ons to a control system, such as sensors, communications, diagnostics, etc., are required, an OMAC-based control system allows the most appropriate technologies to be selected and integrated without relying on specific control vendors to develop custom solutions.

These functional add-ons are required to implement what has been referred to as "model-based manufacturing." In this approach, a model of the process is used to control the process so well that the manufacturer is assured of a good part without dimensional inspection the first time it is produced. Implementation of this approach requires the ability of the controller to accurately measure multiple aspects of the process and communicate these data to the model in real time.

For that, many add-ons can be required, such as process sensors. The model of the process must be implemented in the controller. This is being done today with continuous process controllers in the chemical industry. In the munitions industry, it must be implemented in machinery used to produce batches of energetics and discrete mechanical parts.

One of the potential applications for this controller technology is in the mixing of propellants using a twin-screw extruder. The Army has already developed a process for one formulation using simulation. It plans to use that model to control the process in a small-scale experiment. Once it is satisfied with the results, it plans to incrementally scale up the process to full production. All of these efforts will use the identical math-based model developed in the initial simulation, with incremental updates based on increased experience with the equipment and process. The TIME program has also demonstrated the ability to remotely monitor the process, which is important for safety reasons. TIME implemented a hard-wired version of the monitoring system in 1999 but encountered problems and expenses in attempting to modify the existing controls. TIME believes that the use of OMAC would make these modifications quicker and less expensive.

Another important aspect of open architecture controls is the ease of adding sensors and process diagnostics. When working with energetics, safety is of paramount importance. DoE has succeeded in adding sensors and process diagnostics by means of heavy modifications to an existing controller. However, that controller vendor has gone out of business, and the DoE facilities have not been able to replace the existing controllers with commercial controllers that can perform the needed functions. To maintain the capability, new open architecture controllers are being installed but with similar difficulties and similar modifications required. These same issues exist in the munitions industry. OMAC is intended to allow the addition of appropriate technologies as needed and reduce the risks associated with the availability of vendor support.

A working group of OMAC was formed to develop a specification that defines an intelligent closed-loop controller environment. This environment is to incorporate open architecture concepts and support application portability at the source level, interoperability of modules, and extensibility of controller functionality. The environment is intended for system integrators and applications software developers who will specify standard APIs for open architecture controllers. This working group used the requirements and initial API definitions from the DoE TEAM program as the basis for its work.

In defining this architecture, one of the overriding requirements is allowing one component to be swapped with another, in other words, allowing one implementation of a module to be replaced with another implementation. This requires that the APIs specify how the results of a computation are accessed but not how the calculation is carried out.

The original OMAC requirements specified that the controller be open, modular, and scalable. The openness and modularity requirements were addressed by breaking the controller into several replaceable pieces, defining the state behavior for those pieces, and specifying their APIs. “Scalability,” which was defined as enabling easy and efficient reconfiguration to meet specific application needs, from low to high end, has several dimensions to it. One of these is the ability to extend the APIs of the modules for more demanding, unanticipated needs, while still allowing backward compatibility with existing components. This was addressed by treating the module APIs as object-oriented entities, that had no implementation. Inheritance can be used to extend any given API and, therefore, any given module. A software component, for purposes of OMAC, is required to implement one or more well-defined API sets, have a well-defined state behavior (which is reflected in the individual API sets), and be easily integrated into a controller or exchanged with another compatible component. Ideally these components could be shipped as binary code, rather than source code, allowing software producers to protect their proprietary knowledge.

The APIs, however, exist only as an unproven document (OMACUG 1999), until a reference implementation is built that proves that they work. TIME intends to build a reference implementation controller using the OMAC-defined APIs and make it available to controller vendors as a starting point for their own commercialized implementations. TIME has implemented a reference implementation of an extensible machine tool controller using Java. This controller is based on the OMAC module APIs and component APIs. In addition, TIME has implemented rudimentary integration tools that take advantage of the component APIs, generating application code and checking for system consistency.

The committee believes that Robert Hillaire perhaps best summarizes the state of worldwide open architecture development when he says that “while influential groups are developing the foundation for a more standard controller, they haven’t yet created a useful standard for an open architecture controller” (Hillaire 2000, p. 88).

Munitions Industry Needs and Commercial Controller Capabilities

The TIME program selected two process control examples, that they believe to represent munitions industry challenges that can be met only by using OMACs. These are (1) the melt pour process at the Iowa Army Ammunition Plant, and (2) the use of the twin-screw extruder to process energetics. These examples are presented in detail in Appendix C. The committee has evaluated the control requirements for these processes, as presented to the committee by TIME program participants, and determined that OMAC is not necessary for these applications. The best solution would probably be a Pentium III microcomputer interfaced to a programmable logic control. (It is even possible that a high-end PLC would do the entire task.) Another good approach, although more powerful than needed, would be a commercially available OAC. This would cost only a fraction of the price of bringing OMAC to commercial reality; could be achieved about 2 years earlier; and would have commercial technical support such as manuals, updates, training classes, and technical service staff all over the country.

The TIME program and the committee agree that a superficial market study without in-depth technical analysis of COTS motion solutions can lead to a false sense that the market is full of truly open control products. The TIME program has identified a set of munitions industry control needs and desires, some of which they believe challenge COTS definitions of "open." The list, along with committee comments, follows:

- *Support for model-based control*—The committee believes that any CMC with a disk operating system (DOS) partition can accomplish this.
- *Ability to close loops throughout the controls architecture*—The committee believes that this capability is available commercially.
- *High-speed deterministic communications between facilities*—High-speed point-to-point communications are becoming commonplace. In addition, almost all commercial CMC controllers now include an option for a network card allowing for full access to communications networks.
- *Single paradigm for models, PLC, and motion expression*—The committee believes that this is readily achievable with DOS partition.
- *Mandatory extensibility and portability*—The committee believes that success depends on these capabilities, which are not readily available today but will be commercially available in 2 to 3 years.
- *Hard real-time capability*—The committee agrees that hard real-time control is a required capability of any CMC controller. Such capability is most readily available from established commercial CNC controller manufacturers.

The TIME program maintains that currently available COTS controllers fall short in meeting the needs and desires of the munitions industry, as shown in Table 5–1. The TIME program anticipates that the OMAC, when fully developed, will allow for a unique open solution that meets all of the munitions industry needs and desires. OMAC technology is being developed to allow all control vendors to modify the basic behavior of the controller to fit their methodology, as outlined in Table 5–2. TIME anticipates that the OMAC control architecture, when fully developed, will provide a unique solution to the controls requirements of the TIME program. It will be possible to design OMAC controls with the entire lifecycle needs of the controls engineer in mind and without the legacy constraints that hinder a majority of today's COTS control products. Engineers and designers of control systems will be provided with a single development environment that supports a "train-of-thought" development effort. The engineer will not have to worry about whether the algorithm necessary for the control activity needs data from a PLC or motion system. The engineer will concentrate on the problem and the OMAC environment will assure access to all data necessary to solve the problem. In short, the OMAC environment will allow the control engineer to concentrate on control problems and not the problems of the development environment.

TABLE 5–1 TIME Needs and Desires Versus Current COTS Controller Capabilities, as Expressed by the TIME Program (McWilliams, 2000b)

Munitions Industry Needs and Desires	COTS Controller Shortfalls
Support for model-based control	Model-based controls are constrained by the limitations of the development language. Structured text has only rudimentary math capabilities, thereby limiting the complexity of the model and requiring that the model run on the controller.
Closed loops throughout the controller PLC and motion	TIME's definition of closing loops is not constrained to a single control discipline. No commercial controllers allow for closing loops to levels that include changing control laws and interacting with the entire control architecture.
High-speed interfacility deterministic communications	DCOM is heavily utilized as communications infrastructure and does not meet real-time deterministic requirements because of latency and timeout constraints.
Single development paradigm for PLC, models, and motion logic	The market is led by simple motion and modeling extensions to PLC products. No product provides the combination of complex modeling and motion along with PLC activities. Most vendors require separate products for each area.
Extensibility and portability	Attempts at a portability standard from PLCopen[3] will fall short as long as it accepts partial compliance. Extensibility is limited with the single control product (PLC, motion) and does not allow for product growth between these areas.
Hard real-time capability	Most major microcomputer-based control products do not currently support hard real time across PLC, motion, and modeling.

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[3] Further information is available online at <http://www.plcopen.org>.

TABLE 5–2 OMAC's Planned Features That Meet Munitions Industry Needs and Desires

Munitions Industry Needs and Desires	Planned OMAC Features
Support for model-based control	Introduction of model algorithms is allowed throughout the controller, independent of whether it involves axis position, input/output, or calculated variables.
Closed loops throughout the controller, PLC, and motion	Access to all variables within the control system is allowed, independent of type. Data are not classified as being PLC, motion, or model data. Control algorithms have open access to all data within the control system.
High-speed interfacility deterministic communications	High speed T1 communications between remote sites will be utilized.
Single development paradigm for PLC, model, and motion logic	The OMAC development environment provides a single location for the expression of all logic, independent of whether it is PLC, or model motion. The class definitions for all layers of the control system are immediately available to the controls developer without switching tools.
Extensibility and portability	The JAVA expression of the OMAC controller provides an industry standard mechanism for the control logic of all aspects of the control to move from location to location. The single development environment allows for the extensibility of all aspects of the control system without respect to it being a PLC, motion, or modeling problem. The development concentrates on the control problem and does not have an arbitrary partitioning.
Hard real-time capability	The OMAC is built on top of VenturCom's RTX environment. The RTX environment is recognized by Microsoft and the controls industry as the leading hard real-time extension to Microsoft's Windows NT environment.

COMMITTEE ASSESSMENT OF CONTROLLERS

Needs Versus Wants in the Munitions Industry

The DoD has a strong history of helping U.S. industry by supplying a relatively small amount of seed money to facilitate the development of new manufacturing technologies needed for both weapons production and the commercial sector. Some of these efforts have paid good dividends for both types of users. The efforts that have worked well were in areas where industry could not see the commercial need or could not afford the development investment. Numerical control, Automatically Programmed Tool (APT) programming language, and carbon fiber composites technology are good examples of successful technologies that were given a critically important boost by having their development appended to important defense missions.

The OMAC situation is different. The U.S. CMC industry clearly foresees the CMC becoming nothing more than software inside a standard microcomputer. Furthermore, it is committed to developing such a CMC and has included it in its plans. But today the CMC market is demanding something else. CNCs using microcomputer components and standard commercial software have become so low in cost that they appear to be riding the curve of microcomputer prices. Customers, including big auto companies and small job shops, are buying the largest number of machine tools as commodities (small lathes, small electrical discharge machining units, punch presses, and vertical machining centers), with many suppliers having adequate capacity and quality, and the purchase finally depending only on price. The CMC manufacturer cannot increase prices because of competition. This means that the servo loop cannot be put completely into an existing operating system designed for word processing until it is economical to do so.

This is of little interest to the real users of machine tools. But it presents a real hardship to development engineers. When they want to develop a modified servo loop, they must work in unfamiliar code, which takes them much longer than if they could use their familiar programming languages and operating systems. This has been the constant lament of software developers since the first computers were built. However, the presence of unfamiliar code has not stopped private industry from creating the developments that manufacturers really want and are willing to pay for. For example, many installed flexible manufacturing systems communicate with machines from different manufacturers, talk upstream to MRP systems, manage tooling requirements from the toolroom, report equipment performance to the maintenance department, and optimize their own workloads. These things were difficult for the developers to create but not unusually difficult.

There are many examples of the best U.S. manufacturers using COTS CMC technology and adapting it to their various business strategies. It is never exactly the way they want it at first, but in spite of the lack of the OMAC, they have become best-in-class manufacturers.

Today, a leading job shop in Minnesota uses a COTS flexible machining cell to make aluminum parts. This is not unusual. But this shop will deliver the parts in just a few days from receipt of order, even if they have to write a new part program and even if the part requires many different machining operations all over its surface. Their competitors take weeks to do the same thing. The Minnesota shop can do this because they have taken the best of standard machining capability and the best computer-aided programming software and learned how to use them together. They can manufacture any aluminum part that fits on their machines at an economic order quantity of one, with no time lost for setup changeover. Their machines are producing a wide variety of parts, 24 hours per day, 7 days per week, with over 90 percent uptime. It was difficult for the manufacturing engineers to develop this capability, but their management focused on the right problems and the engineers solved them. Now they are unique in their capability. They are the most flexible and responsive supplier in their market niche, and they did it without the convenience of the OMAC for their manufacturing engineers.

Conclusion: TIME should be taking full advantage of COTS systems and technologies that can directly address critical Army production problems, rather than investing in new technology development where COTS solutions exist.

The munitions industry can make dramatic improvements in their shop floor operations by buying, installing, and integrating the excellent machine tool controllers now available from commercial suppliers (e.g., GE/Fanuc, Mazak, and Mass). In recent years these controllers have been expanded in their capability, file handling operations, sensor integrations, and integration with higher-level CAD/CAM systems. They are used on a day-to-day basis by advanced machine shops all over the United States and in other countries. Advanced open architecture controllers are available from several companies such as Delta Tau and MSDI, but these are not needed for the TIME mission. Even more experimental platforms—such as the OMAC—are available from research laboratories, but in the opinion of the committee, these are well beyond the current scope and needs of TIME.

Commercial off-the Shelf Controls Versus Industry Needs

Until the mid-1980s, all of the CMC machines supplied by machine tool vendors had closed architecture controllers provided by companies such as Fanuc, Mazak, and Cincinnati Milacron (now Acramatic Siemens). This meant that a user or programmer was constrained to work with the predefined library of G and M codes (now the RS-274 standard) that were supplied with each vendor-specific controller. This resulted in limited library functions that were written in local formats. They were not open to third-party software developers who might have supplied routines in the C programming language for new CAD information or to the new machining sensors coming onto the market. This was sometimes a problem for companies with highly complex or rapidly changing machining needs. The limited library functions written in local formats do not generally cause problems for standard day-to-day machining operations. Likewise, they are highly unlikely to cause problems in controlling the relatively straightforward processes and machining operations typically found in munitions factories. Most of these processes and machining operations have been performed for decades in Army munitions plants without the benefits of controllers of any type.

Machines with recent open architecture controllers (e.g., Greenfeld et al. 1989) allow faster access between high-level computer-aided design (CAD), computer-aided process planning, and computer-aided manufacturing (CAM). For example, (1) highly complex casting geometries in CAD can be readily converted into cutting tool motions for mold making; (2) nonuniform rational B-spline curved surfaces can be downloaded from CAD and executed on a standard three-axis milling machine (Hillaire et al. 1998); and (3) today's open architecture COTS controllers allow a machine tool to automatically compensate for errors in positioning of the work piece and make possible the active control of the machining process by accepting input from external sensors. This results in faster production, more flexibility, and more opportunity for on-machine inspection and quality control.

These are highly sophisticated examples of tasks that can be readily accomplished when today's COTS CAD/CAM packages are linked to well-documented COTS Fanuc, Mazak, or Cincinnati Milacron CMC controllers. These interconnected systems can be seen all over the world carrying out first-class machining. U.S. automobile companies use such environments for daily production, and the machine shops in Silicon Valley that supply the large semiconductor equipment manufacturers use standard CAD/CAM packages linked to standard Fanuc, Mazak, or Cincinnati Milacron CMC controllers.

In the last few years, the controller industry has brought to market new controllers that satisfy many of the goals of OMAC and many of the needs of the munitions industry. Commercial vendors are moving on their own to fill the needs of the marketplace. In the committee's opinion, what is available now is likely to do everything needed by the Army for the foreseeable future, even if there are some extraordinary requirements for the munitions industry.

The TIME program cited, as an example, the need for an OMAC so that twin-screw extruders can be operated by remote control (for safety reasons) to make identical batches of the approximately 120 energetics formulations in the munitions inventory today, with virtually no operator training regarding the specifics of each formulation. The committee believes that this task can be successfully performed using a combination of today's COTS controllers and today's COTS Internet communications technologies. This opinion was reinforced by Tom Gassenbeck,[4] president of E-Manufacturing, a Canadian company. This company has, for several years, been interfacing controllers, such as those sold by Fanuc, to networks. The COTS technologies being sold by E-manufacturing demonstrate that OMAC technologies are not required for interconnection of equipment in the munitions industry.

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[4] Personal communication with Richard Kegg, TIME Committee Member, August 24, 2000.

The NRC committee is critical of TIME's heavy financial investment in the ongoing OMAC development activities. The OMAC work to date may be of good quality and may ultimately benefit both users with highly sophisticated requirements and users with less sophisticated requirements, as typically found in the munitions industry. The committee agrees with the TIME program that if and when the OMAC development effort is successfully completed and when a wide variety of proven components are commercially available, the effort to modernize the munitions industry would benefit in terms of (1) lower-cost hardware and software due to increased head-to-head competition, (2) easier system integration and easier integration of enhanced functions, (3) opportunities for third parties and end-users to incorporate custom application controls and strategies, and (4) faster product realization cycles.

However, it appears to the committee that very substantial additional investments will be required before these benefits can begin to be realized, and it is not at all clear to the committee when, if ever, the OMAC will be commercially adopted. Although techniques for the transfer of technologies from laboratories and their implementation into commercially useful products have improved somewhat in the last decade, technology transfer remains an art as much as a science. Many barriers are typically encountered when technologies are transferred from one organization to another, and it is anticipated that the OMAC will be no exception. According to Rob Kling, a professor of information science and information systems at Indiana University, there is a "big gap between the conception and the execution" of any new computer or software system (Manufacturing News 1999). Thus, commercialization and implementation are likely to be major issues. One way to reduce these problems is to involve the commercializer in the development project. This means, at a minimum, that it must have a voice in planning and must be able to closely follow the development work. The best way for this to happen is for the commercializer to license the rights and commit substantial financial and human resources to the effort at an early stage in the development process. Although there are many participants in the OMAC development effort, LLNL remains by far the dominant one. TIME has yet to find a commercializer for the OMAC that is willing to invest substantial time and resources. OMACs may someday be a major improvement over the COTS microcomputer-based CNCs that are offered today by the machine tool controller industry. However, based on the experience of the controller industry, the OMAC will not be simple and inexpensive to complete. This raises the concern that the OMAC may be many years from having a validated architecture and a multitude of thoroughly validated COTS OMAC products from which the munitions industry could select and use with confidence, knowing that manuals, technical service, and continuing product improvement will be available as needed.

For example, the committee is concerned that safety issues in an open environment must be thoroughly addressed and validated before components are implemented into the already dangerous munitions manufacturing industry. The common API must include a complete firewall between the user's custom applications and the control builder's real-time operating systems. Reuse of common hardware and software components to construct a controller can lead to unexpected results if safety considerations are not factored into each component's design, accounted for in the integrated solution, and thoroughly validated for all conceivable operating conditions. System safety, traditionally the responsibility of the machine tool builder must, with the advent of OMAC, become a major skill and responsibility of the system integrator.

Today's munitions factories are vastly behind the state of the market, having little or no CMC-controlled equipment and virtually no computers. There is a pressing need to install today's COTS CMC controllers with their very adequate links to CAD/CAM systems, as described in other parts of this document. The Army, through TIME, should also be investing in basic microcomputer platforms and Internet connections to begin to bring some of the munitions facilities up-to-date. OMAC can be compared with a Grand Prix race car. It is highly desirable to have, but the needs of the munitions industry are far less demanding, much like day-to-day commuting for which a standard (COTS) sedan is sufficient.

It is possible that the control capabilities required for processing advanced energetics and for manufacturing advanced semicustom smart munitions might be greatly enabled by the successful completion of the OMAC. However, no such needs or requirements were presented to this committee and, until the requirements for these products are further defined, such requirements remain speculative in nature.

One advantage of OMAC is that its implementation can be a gradual process. Control components can be implemented gradually as they become available or as needed to achieve the level of openness required by the application. Thus, unless there is a compelling need that cannot be addressed by COTS controllers, there is little need for massive government funding of OMAC to further its development. Rather, the munitions industry can be upgraded according to a prioritization of needs using COTS technologies. OMAC technologies can be inserted as needed when the technologies have matured through commercial development and validation, such that there is a high degree of confidence in their reliability and suitability. The committee believes that OMAC, in the near term, has the potential to provide more benefits to companies that already have state-of-the-art COTS controllers and CAD/CAM systems linked to their supply chains, than to the munitions industry, which has yet to implement these basic capabilities. The Army should not be investing in advanced controller technologies when funds for basic upgrades to the munitions industry, which should have higher priority, are virtually nonexistent.

The committee also had difficulty reconciling the extensive focus of TIME resources on the development of real-time OMAC controls when the DoD munitions replenishment scenario anticipates a process requiring up to a year to get replenishment lines up and running. It appears to the committee that, in an era of limited defense budgets, progress in implementing today's COTS technologies will do far more to assure rapid scale-up for replenishment than trying to develop OMAC technologies that may ultimately offer only marginal advantages.

Similarly, the committee believes that the melt pour process line at the Iowa Army Ammunition Plant can be remotely operated successfully and safely using COTS technologies and that only slight improvements are likely in the near future with OMAC technologies. For instance, processes of similar complexity in the paper industry are successfully controlled using today's COTS technologies. It should be pointed out that according to the TIME program (Frampton and McWilliams 2000), this state-of-the-art process line presently has no modern process controls. It is run directly by operators with the aid of thermometers and the experience and judgment of the operators concerning properties such as the appearance of the "applesauce-like" texture of the mixture of molten trinitrotoluene (TNT). It was reported to the committee that the process is highly dangerous to the operators and frequently yields defective product, which, if allowed to leave the facility, would pose significant hazards to the (warfighter) users. It was reported to the committee (Frampton and McWilliams 2000) that the Army has efforts under way to document this manual process as a first step toward implementing up-to-date control technologies. The committee believes that perhaps someday this process may be more elegantly controlled using the OMAC, but it is not needed. Process control experts at corporations such as Honeywell International and Foxboro[5] design and install control systems for processes of equivalent or greater complexity on a routine basis.

Recommendation: The committee recommends that the Army issue contracts to commercial process control experts to implement modern, commercial-off-the-shelf control technologies on energetics process equipment in government-owned munitions manufacturing facilities.

The committee encountered considerable controversy regarding OMAC. Enthusiastic arguments were given for termination of OMAC, as well as for increasing its support. Opinions ranged from "badly needed by the Army and by industry," to "totally unnecessary." Some perceive the OMAC project making substantial progress. Others view it as a government-funded project that has been under way for almost a decade and has not provided any payback. Some believe that OMAC will someday offer substantial benefits. Others believe that it will result in little value to routine users of CNCs. Some say that OMAC will offer substantial advantages over today's COTS controllers, while others say that commercial industry's latest offerings will do almost everything that OMAC will someday do at a fraction of the cost of bringing OMAC to commercialization. Some believe that OMAC offers such high commercial value in the marketplace that large companies will adopt it. Conversely, others feel that the development effort will cease if government funding is stopped.

It is outside of the mission of this committee to settle the overall debate regarding the ultimate value of OMAC for commercial and defense production and whether the government should continue to subsidize OMAC development. However, the committee has studied the matter sufficiently to form some conclusions and recommendations regarding the importance of the OMAC to the munitions industry today.

First, there appear to be serious questions regarding the amount of investment that is justified in rehabilitating and upgrading the existing, deteriorating munitions manufacturing base. The committee was shown no evidence of recent, detailed studies of specific munitions manufacturing equipment needs and process needs in response to up-to-date warfighting scenarios and emerging energetics and smart munitions technologies. Such studies are important for assessing risks and setting investment priorities and should include a bottom-up assessment of controller requirements for the munitions industry over the next 10 years. Specifically identified needs should be compared, application by application, with the capabilities of COTS controllers. Although it may well have made sense that initial OMAC development work focus on the development of an overall framework for open architecture, the committee strongly questions the investment of TIME program funds in OMAC development prior to a determination of clearly identified munitions industry needs (as opposed to desires) for such technologies. Such studies should be completed before any final decision can be made regarding the appropriateness of further Army investment in OMAC. The committee has not been made aware of any munitions manufacturing need (as opposed to wishes) that cannot be adequately addressed by today's COTS controllers.

Recommendation: As part of overall munitions industry planning, the TIME program should conduct a bottom-up munitions industry study of specific machine and process controller requirements for the next 10 years.

Recommendation: TIME should divest itself of further OMAC development and proceed immediately to transfer the OMAC, as is, to commercial sponsors.

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[5] These corporate examples in no way constitute a recommendation by the NRC.

6

Demonstration and Validation

INTRODUCTION

The Totally Integrated Munitions Enterprise (TIME) program is attempting to develop and beginning to implement a highly complex, integrated system that will become one of the cornerstones of U.S. national defense. Although the Army would not necessarily be precluded from reverting back to today's "manual" methods of producing munitions if the system failed, significant benefits of the integrated enterprise, especially faster response at lower cost in the event of national need, would likely result in increasing national reliance on its capabilities. Therefore, the integrated enterprise must be robust and sufficiently validated under a variety of conditions, so that there is a high probability that the system will perform properly when needed. Assurance that the enterprise will work under wartime conditions, which could result in damage to U.S. infrastructure or system impairment due to cyber warfare, makes validation more difficult.

Thus, the TIME program must (1) strive to create a loosely coupled integrated system with sufficient parallelism to make it robust, and (2) extensively validate the system over time, as the constituents of the system and as the scenarios under which it might be used evolve. Thus, demonstration and validation of integrated munitions enterprise concepts will play a critical role in the TIME program.

In assessing efforts by the TIME program to demonstrate and validate key technologies, the committee turned first to definitions. The committee defined "validation" as the means of confirming that an approach is well grounded, justifiable, and correctly derived from basic premises. "Demonstrations," on the other hand, exercise some segment of the system under a selected set of conditions, thereby serving to illustrate or provide conclusive evidence that an approach can be made to work. Demonstrations do not generally attempt to build from first principles a series of robust, logical arguments that mathematically prove that an approach will work under a wide variety of conditions or, ideally, under all foreseeable conditions.

To date, TIME has focused on demonstrations, which are reviewed and assessed in the next section. Little attention has yet been paid to validation, although the TIME literature uses this term. Specific suggestions on validation are offered in the last section of this chapter.

DEMONSTRATION PROJECTS

Project Selection

In response to its funding history, which has consisted primarily of a series of “one-time” congressional mandates without assurance of future funds, the TIME program has correctly been highly sensitive to the need to demonstrate short-term successes. TIME program managers were forthcoming in pointing out that if a steady funding stream were assured, they would organize the program in a more conventional manner, with less emphasis on short-term successes that might not lie on the critical path. For instance, the TIME program presented no methodology, other than the availability of technologies, for its selection of demonstration projects. This approach is well below commercial industry standards that typically rank candidate projects based on criteria such as (1) return on investment, and (2) criticality of technologies to the overall program. Without the use of such selection criteria, there is substantial risk that work on these projects may be of low value to the overall TIME program, resulting in program delays and lower overall returns on investment.

Nonetheless, with the exception of the Open Modular Architecture Controller (OMAC) project, selection and execution of demonstration projects appears to be one of the strongest aspects of the TIME program. For the most part, TIME has chosen projects that could be quickly brought to fruition or that incorporated pieces of technology that had a significant head start before the TIME program began. These projects have provided an excellent means for soliciting external reactions to the program while building stakeholder enthusiasm and support.

The TIME program is using real-world proof-of-principle projects, integral and concurrent with the development of major facets of the program, to demonstrate key capabilities. These projects enable testing, feedback, and improvement by the developer through testbed applications and they aid both the developer and the (U.S. Army) Tank-automotive and Armaments Command/ Armament Research, Development, and Engineering Center (TACOM-ARDEC) in determining the degree of success and correctness of direction of selected TIME elements.

Demonstration activities typically include efforts to accomplish the following (Burleson 1999b):

- Procure testbed integration components.
- Configure and maintain testbeds.
- Support integration, validation, and benchmarking.
- Incrementally include product realization tools as they become available.
- Incrementally include OMAC capabilities on the shop floor as they become available.
- Provide feedback to design and implementation activities.

These demonstration projects also serve as a means to begin to implement some of the key technologies into everyday practice with the intent that they will stay in place and remain operable as part of the gradual process of upgrading the munitions manufacturing base. The TIME program, depending on funding, has planned six major demonstrations of its integrated architectures and technologies outside of the laboratory (Burleson 1999b):

1. Concept validation,
2. Miniaturize global positioning systems,
3. Scranton/General Motors Powertrain (GMPT) product data exchange,
4. M42 grenade,
5. Explosively formed penetrator, and
6. Twin-screw extruder.

Each of these demonstration projects has scheduled milestones and specific technology objectives. Many of these projects consist of a 1-year primary thrust plus scheduled follow-on tasks that extend beyond the initial demonstrations. In some cases, the follow-on tasks are designed to upgrade system capabilities as they become commercially available.

The primary purpose of these demonstration projects is to accomplish the following:

- Identify problems and provide valuable feedback to design and implementation teams within the TIME program.
- Help to ensure deployment of only robust instantiations of the TIME architecture.
- Focus the diverse efforts of TIME program participants on specific, measurable goals and schedules.
- Demonstrate progress and the potential value of the TIME program to diverse constituencies, including the sources for ongoing funding.
- Begin the deployment of TIME technologies and capabilities to production programs.

Concept Validation

The concept validation project was organized into four initial segments:

1. *OMAC version 1.0, mill and piece parts*. Scheduled for program years 1 and 2;
2. *Electronics*. Scheduled for program years 2 and 3;
3. *OMAC version 2.0, mill and piece parts*. Scheduled for program years 2 and 3; and
4. *OMAC version 2, lathe and assemblies*. Scheduled for program years 3 and 4.

The purposes of the concept validation project are to test the TIME architecture incrementally in a controlled environment and also to test the TIME toolset, including the product realization technologies, a network testbed, and the OMAC, as the tools became available. Thus, it is intended that the project demonstrate a collaborative design and manufacturing environment, a fully networked infrastructure with application servers, and structured document archiving.

Miniaturized GPS

This project will extend the TIME product realization toolset into electronics manufacturing. The 5-year plan will begin with the application of TIME tools for requirements definition and culminate in a production facility that can produce low-cost modules for a wide variety of munitions applications (ManTech 1999). The objectives of the miniaturized GPS project are as follows (Burleson 1999b): (1) Use a previous-generation GPS subsystem as a vehicle for electronics miniaturization (redesign the module for use in munitions). (2) Drive modularization of design for multiuse circuits in families of applications. (3) Demonstrate flexible manufacturing for small lot electronics manufacturing. (4) Demonstrate the extension of the TIME toolset into electronics manufacturing.

This demonstration project was initially planned for early in the TIME program but is now in the planning phase.

Scranton/GMPT Product Data Exchange

This is one of an ongoing series of demonstration projects being conducted at the Scranton Army Ammunition Plant that are designed to gradually integrate the facility into the munitions enterprise. The objectives of this project were to demonstrate the capability to (1) integrate an initial collaborative toolset into the Scranton TIME network; (2) electronically transfer product and process design data among ARDEC, Scranton, the Louisiana Center for Manufacturing Sciences, and a potential commercial replenishment manufacturer, GMPT; and (3) manufacture discrete parts (a mortar adapter) using those data at both Scranton and GMPT (Burleson 1999b).

The project has been essentially completed, successfully demonstrating the following, in sequence (Stephens 2000):

- Remote downloading of design files from the TIME file server via the internet,
- Translation and processing of the computer-aided design (CAD) files,
- Performance and verification of tool simulation,
- Modification of machine instruction files,
- Subsequent uploading of computer-aided manufacturing (CAM) files to the TIME file server,
- Downloading of CAM files to the shop floor,

- Programming of the commercial-off-the-shelf (COTS) machine controller, and
- Manufacture of parts using all of the above data.

M42 Grenade

The M42 grenade project focuses on sharing of a shop traveler via a virtual enterprise. Its primary objectives are the following (Cary 2000) (1) Demonstration of the TIME surge manufacturing concept of using dual-use suppliers to broaden the munitions manufacturing base, (2) Establishment of a secure Web-based virtual environment at Primex (a routine munitions supplier) and GMPT (a potential dual-use supplier), (3) Demonstration of a Web Integration Manager and associated cockpits; (4) Electronic capture of Primex's manufacturing process for the M42 grenade, (5) Demonstration of the basic TIME collaborative environment and capability to transfer both CAD and CAM information, (6) Demonstration of an OMAC front end on an existing computer-numerical-control lathe at Primex, and (7) Building on these capabilities with these key participants in the TIME replenishment effort.

The committee noted that this demonstration project served to identify an issue that TIME thus far does not appear to have addressed, that of design and fabrication of custom metalworking tools and dies. Most of TIME's metalworking efforts to date have dealt with relatively straightforward metal removal and shaping using readily available COTS tools for cutting, knurling, grinding, facing, boring, and drilling on mills and lathes. Preparations for fabrication of metal parts at remote, dual-use sites becomes more complex when, as in the example of the M42 grenade, custom dies are required for cupping and coining. Fortunately, such dies for fabrication of munitions are typically relatively straightforward, but they can nonetheless require both redesign by the dual-use supplier to match its specific equipment interfaces and fabrication by increasingly scarce custom tool and die makers. Identification of unforeseen problems, such as the issues associated with tool and die design and fabrication, points out the importance that the TIME program has correctly been placing on demonstration projects. It also identifies a need for the TIME program to devote ongoing attention to parts of its dual-use supply chains that are typically seldom used or nonrecurring but nonetheless on the critical path for production.

Recommendation: As replenishment suppliers are added to the enterprise, the TIME program should focus attention not just on integrating recurrently used portions of dual-use supply chains, but also on nonrecurring and seldom-used suppliers, such as tool and die fabricators that can play a critical path role in the rapid ramp-up of replenishment capabilities.

Explosively Formed Penetrator[1]

This project is focused on the issues associated with extending the virtual enterprise to the shop floor. It is scheduled for completion in December 2000 and is designed to test a TIME toolset in a production environment. Aerojet will demonstrate the flexibility of the OMAC, version 1, for advanced munitions components (ManTech 1999). Plans are to (1) install the TIME collaborative environment at Aerojet, (2) incrementally introduce product realization tools as they become available, (3) establish and train an integrated product team, and (4) incrementally include OMAC capabilities on the milling machine as they become available (Burleson 1999b).

This project will also serve as a means to evaluate use of the TIME collaborative environment in the fabrication of a sample product. The team has succeeded in electronically forwarding CAD data for a novel explosively formed penetrator design from ARDEC in New Jersey to Aerojet in California. Aerojet, in turn, forwarded the CAM data to Lawrence Livermore National Laboratory (LLNL) where the penetrator was machined on a mill controlled by an open architecture controller (OAC) developed by LLNL.

Twin-Screw Extruder

The TIME program is also carrying out the Picatinny/Thiokol/Stevens twin-screw extruder project. The nation’s current energetics production base is decades old. The facilities were designed for large production quantities and are inflexible to varying formulations of propellant, explosive, and pyrotechnics. Recent procurements of energetics have decreased to such a low level that production facilities are operating at a small fraction of total capacity. This is causing the cost of producing energetic materials to reach unaffordable levels, necessitating significant changes within the industrial base to maintain a viable energetics production capability in the United States. In response to the current business environment, efforts to develop new energetics materials, and a trend toward “designer munitions,” the industrial base must be modified to cost-effectively produce a wider variety of new and existing products in smaller quantities. To do this efficiently, the Department of Defense (DoD) will have to partner with private industry and academia and leverage a substantial commercial infrastructure to manufacture the required energetic materials.

A process methodology has been developed and demonstrated under the TIME program that quickly transitioned technology from small-scale R&D quantities to large-scale production. A virtual enterprise network was installed that provides a link between industry, government, and academia to transfer real-time data between sites. This, according to the TIME program, will reduce product development time from 5 years down to approximately 2.5 years. It will

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[1] It should be noted that the term “explosively formed penetrator” does not mean that the device is made by the munitions supplier by explosive forming. Rather, the “hockey puck” shaped piece of metal is typically produced on a milling machine. It is explosively formed into its final shape during detonation of the munition in the field.

also significantly improve processing safety and reduce hazardous waste streams.

This project addressed the issues in two ways. First, a new CL-20-based explosive formulation was developed using the TIME methodology. Second, the TIME network was utilized with the current production base to improve the propellant manufacturing process. CL-20 is a state-of-the-art, high-energy explosive compound that is extremely sensitive to dry handling. The focus of this project was to demonstrate the safe reproducibility of CL-20 when scaling up to production quantities.

The project successfully demonstrated the use of modeling and simulation tools for product and process development, including modeling the crystallization process and determining the critical relationship between physical and chemical characteristics of the material on a microscopic scale and correlating these to bulk characteristics on in-process and end-product materials. The TIME network will be used to link the model to both the bulk laboratory experiments and the production of CL-20. The TIME program has already successfully demonstrated the continuous production of small batch lots of energetics at remote sites using real-time monitoring and control from a central location.

The Army's Modular Artillery Charge System is currently using M30A1 triple-base propellant in the XM232 charge and has decided to utilize PAP-7993 propellant in the XM231 charge. Large quantities of these propellants are currently being produced using a batch method, and there tends to be variability in production lots. A major contributor to variability is the design of the die used to form the final propellant shape. By applying the methodology developed under the TIME program, a better understanding of the process can be achieved and improvements to the existing process can be implemented. Once the process is understood, new technology can be developed to enhance the process and eventually reduce the variability and cost of the material.

By applying this technology, warfighters will be provided with advanced energetic materials for their weapons systems with significantly enhanced effectiveness and survivability, and the energetics industry will have the ability to bring new energetic materials to the warfighter faster than ever before. Further details regarding the twin-screw extruder project are presented in Chapter 5 and Appendix C.

The TIME program intends to modify the twin-screw extruder TIME network to incorporate the OAC module developed for program logic controller interface. This effort is designed to demonstrate the ability to control the extrusion and mixing of energetic formulations through sensor feedback to a mathematical model and automatic adjustment by the control system of key parameters. This demonstration is fundamental to proof of the base concept and essential prior to implementation of the model-based control approach on production lines.

Another TIME project is taking this concept of model-based control and applying it to a melt pour production line at the Iowa Army Ammunition Plant. The operation's control needs are described in depth in Appendix C. Following completion of this design and the completion of the twin-screw extruder project, a project to execute the melt pour design as a prototype project funded through Production Base Support funding is anticipated.

Summary of the Demonstration Projects

These projects demonstrate several virtual enterprise concepts, including the ability to leverage commercial facilities for surge capacities. With the completion of these projects, the concept of transferring metal removal operation processes from existing metal part producers to a commercial site and the concept of using commercial nondefense producers for expansion of capability for replenishment purposes will have been demonstrated.

Conclusion: The TIME program is to be commended for its focus on demonstration projects as a means to try out complex integrated enterprise systems in a real-life environment and as a means to identify potential problems prior to full implementation and use.

Recommendation: When a long-term strategic plan for TIME has been developed, after the Army has assumed ownership of TIME, and as the TIME program moves toward the implementation phase, increased program priority should be given to demonstrations and system validation, so as to verify that the concepts can be made to work and to reduce the chances for unforeseen system problems.

Recommendation: The TIME program should, on a regular basis, review its goals and objectives, as well as its technology path for achieving these objectives, so as to avail itself of the latest, appropriate, well-proven COTS technologies from commercial industry.

To date, validation of TIME technologies has centered on demonstration projects. This is a good first step. It is an effective means to assure that the tools and technologies can be made to work in the munitions industry environment and to demonstrate that the objectives of TIME are being met in a usable fashion. However, there can be a natural tendency to demonstrate and forget. Each demonstration must be viewed as a link in a chain so that, as each element in the “demonstration matrix” is completed, the overall system is formed in place. It is important to identify and structure this process through to its ultimate form. It is true that the process may change significantly over time, but the process of demonstrating subsystems before they are integrated into the operational structure will tend to help identify issues that need to be addressed, especially the interactions between subsystems. It should also be noted, however, that demonstrations are merely “existence proofs” that show that the process will work under a narrowly defined set of conditions. The committee believes that far more validation is needed before substantial resources are committed to broad implementation.

VALIDATION

The committee recognizes that, in the worlds of manufacturing, business, and e-commerce, new tools, techniques, and architectures are seldom validated back to first principles for all foreseeable applications and conditions. Such validation could, in many cases, consume more time and resources than were required to initially develop and demonstrate the technologies. However, the committee believes that it is important for the TIME program and the Army to identify potential limitations and vulnerabilities that may be inadvertently built into the integrated munitions enterprise upon which the United States will base a significant portion of its national security. Without extensive validation, defects in this highly complex system may not become evident until the system is called upon to meet an urgent national need.

Validation of Product Designs and Manufacturing Processes

There are several levels of validation that the TIME program must consider. It is important that the disparate, individual systems that make up the integrated enterprise be validated to assure that they properly perform their defined tasks. Is the software error free and the hardware defect free? It is also important that the interfaces and interoperability of these systems be validated to rigorously work together within the enterprise under a variety of conditions.

More fundamentally, however, the TIME program shares responsibility with other DoD programs for electronically documenting munitions designs and manufacturing processes and ensuring that product manufactured at multiple locations, using a mixture of modern, antiquated, mothballed, and dual-use equipment along with materials from a variety of suppliers, will all consistently yield products that fully meet DoD specifications. Part of the problem is pedigree. If, for instance, processes are developed for fabricating a part on an old piece of equipment and the munitions enterprise wishes to produce the identical part on new or different machines, possibly with new or different controllers, is the new part really the same as the old? How can this be validated for safety, reliability, and performance without the building and field testing of large quantities of prototypes? Machining knowledge and processes are a complex, interactive sum of multiple factors such as geometry, "features," materials, control characteristics, physics, rigidity, and tools. Thus, to rigorously automate a process or to transmit sufficient information to a new machining site can be a daunting challenge.

Validation Details

Munitions designs at government-owned/government-operated facilities, as described by participants in the TIME program, have traditionally been documented on paper or Mylar. Efforts are under way by the Army to scan these documents into an electronic format. Likewise, according to TIME participants, parts of some of the manufacturing production processes are documented on paper or Mylar. Others are relatively undocumented (McWilliams 2000a). Munitions experts are retiring or are being laid off as funding declines. Capturing production methods is almost always a difficult and complex task. Thus, TIME faces a serious challenge to (1) electronically capture all of the information that is required to manufacture the product, (2) validate on the original manufacturing equipment (if still available) that all of the necessary data have been correctly captured, and then, (3) using these data, validate that product produced on different machinery, by different operators, and using materials from different suppliers will meet all specifications. Although many of the metal parts currently used in the munitions industry are relatively straightforward to produce, slight variations in energetics processing can produce catastrophic results (McWilliams 2000a). Newer generations of increasingly smart munitions tend to be more complex. Hence, there is an increasing need for extensive validation. As equipment is modified or replaced, which can happen with relative frequency in dual-use operations, the validation process must appropriately keep up with the changes.

Product validation requires extensive attention to details, documentation, and the implementation of in-process and finished product testing. The munitions industry should pay special attention to assure that the workforce is properly skilled in the quality assurance function.

Appropriate validation of a massive, highly complex system, such as the munitions enterprise, requires attention to myriad details, concepts, and challenges. For example, capture and effective dissemination of knowledge is essential, especially for rapid replenishment. “Knowledge” can be thought of as information organized in context. Although tools are being commercially developed to capture knowledge, to date they are preliminary at best. “Intent” can play important roles in the understanding of transmitted information, yet to date intent cannot be effectively captured and transmitted. These technology limitations add risk to the TIME approach, which relies heavily on the timely transmission of product and process information from one site to another. Extensive, ongoing validation will be required to reduce these risks and to increase confidence in this approach.[2] Validation will also be required to assure that all necessary process knowledge, some of which may be considered proprietary by routine producers of munitions, is transferred to replenishment dual-use suppliers in a timely manner. Exercising the process on a regular basis and evaluating the output can help to validate the completeness of the data packages in advance of need.

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[2] These comments by the committee are not intended to criticize the TIME integrated enterprise approach, but rather to assist in identifying vulnerabilities that must be addressed.

Recommendation: Substantial resources, including funding, must be made available to the TIME program to validate the integrated munitions enterprise so that it can be trusted to perform appropriately when needed.

Controller Validation

The model that OAC developers are building on, using application program interfaces (APIs) and separate software modules, can never be fully tested. MS Windows and Windows NT use the same model and, despite extensive user experience and testing done by Microsoft, desktop computers using these systems crash from time to time. Adding new software and hardware, as OMAC developers are doing, only adds to the risk, no matter how well they validate. Everyday experience with current desktop systems demonstrates that this is the case.

The difference is that system crashes can be a significant cost and safety problem in the controller environment. They happen with today's OACs. Although the argument is made by proponents of the OAC that crash problems are caused by users, the systems tend to be made more complicated than necessary by adding additional software that is not needed for the controller functionality. If well-tested, commercially available software that is not even using the real-time kernel cannot be added to OAC systems without risking system failures, then the committee questions the rationale of an OAC.

In the Microsoft model, the key intellectual property of the company, the core functionality of Windows or NT is tightly controlled. This is one of the primary differences between MS Windows and Unix. There is only one version of MS Windows and many more applications are written for Windows than Unix because of this. Source code for Windows has never been released and because of that, it is said by some that MS is not sufficiently open, thereby restricting those who would write applications for it. (This is part of the current litigation between the federal government and Microsoft). This is the same argument made by proponents of the LLNL version of OAC for continuing their work. Since the LLNL OMAC version will be "open" as in the Unix model, to which version of the core controller functionality will controller add-on applications providers be writing code? The answer can perhaps be found in the operating system "wars." They will write applications for the core functionality that holds the biggest market share. Hence, they will tend to write applications for the current market leaders, Fanuc and Siemens, unless a huge user group forces the issue.

Following the "open controllers are like MS Windows" line of argument put forth by the OMAC developers, who is the Microsoft for this application? Who will be responsible for testing the APIs? Who will assure that the system is robust? Is it the national laboratories, the as yet unidentified companies who may someday want to commercialize the OMAC, or might it, by default, end up being the TIME program? Despite the possibility of extensive testing in government laboratories, it appears unlikely to the committee that sufficient funds will be provided for the proposed OMACs to be sufficiently validated to pose minimal risk to the user.

Assessment of Validation Plan

To date, the TIME program has done little to outline plans for—or implement—a validation plan. The plan should start with the selection, wherever possible, of commercial industry-proven tools and concepts for the integrated enterprise. Ideally, these tools should be proven, back to first principles, to operate in all foreseeable use environments. All new tools and concepts developed by TIME should likewise be thoroughly proven out before being inserted into a production environment. Then all of these parts of the enterprise system should be proven to work together under all foreseeable scenarios. This validation process should include the introduction of system faults to determine how well the system responds to faults and whether there are single points of failure. This thorough validation process, which is essential to have a high degree of assurance that the system will work, especially in times of crisis, can be extremely expensive. The cost of validation could be equal to or exceed the development costs of the tools and components.

Although a rigorous validation of such systems is seldom undertaken due to time and cost, it is a topic that should not be ignored. Validation efforts should be commensurate (proportional) in magnitude to the criticality of system performance, especially in times of crisis. Should the validation of munitions manufacturing systems be as extensive as those undertaken for nuclear power plants, missile launches, or nuclear weapons performance and safety? Probably not. However, the importance of munitions manufacturing and the magnitude of potential investments in implementation make it abundantly clear that an extensive validation effort, well beyond the several demonstration projects envisioned to date by the TIME program, is justified. Recent highly publicized problems in the implementation of enterprise resource planning (ERP) systems at major U.S. corporations come to mind as examples. Such problems can be costly for commercial industry but have the potential to create a national disaster if not identified and resolved in advance of use in a munitions replenishment effort.

Dr. George Hazelrigg of the National Science Foundation, for example, in recent papers (Hazelrigg 1999a and 1999b) has identified flaws in frequently used engineering design and manufacturing techniques, such as quality function deployment, the Taguchi Loss Function, and the Pugh Selection Matrix, that can result in conflicting or misleading answers. Similar questions have been raised regarding the models and simulations used in engineering design and analysis as well as frequently used ERP, supply chain management, and other computer systems that may well form part of the backbone of the integrated munitions enterprise.

Conclusion: The integrated munitions enterprise will be especially vulnerable to unanticipated failures because it will consist of a large number of disparate, evolving systems, segments of which are primarily utilized by dual-use suppliers and may rarely be exercised in conjunction with other parts of the integrated munitions enterprise.

Recommendation: It is extremely important that the integrated munitions enterprise be well validated, before and during implementation, both as components and as a system. It is also extremely important that the system be regularly exercised to identify and resolve problems as participants are added and removed from the enterprise and as individual computer systems change or migrate to newer versions.

Recommendation: The validation projects of the TIME program should be subject to review by DoD managers at an appropriate level to assess the projects' contributions to the management of munitions across all military services so that appropriate program changes can be made to assure that the services needs are met.

7

Benchmarks and Metrics

INTRODUCTION

The Totally Integrated Munitions Enterprise (TIME) program defines "benchmarking" as the act of determining a state or characterizing something for use in making comparisons, achieving definition, or establishing a reference basis (e.g., capability or performance levels of a set of similar products offered by competing companies) (Raytheon 2000). The TIME program has, as a cornerstone philosophy, the use of up-to-date commercial-off-the-shelf (COTS) technologies whenever possible and development of new technologies only when such capabilities are not commercially available. Thus, benchmarking against both COTS and up-and-coming commercial technologies should be a critical and ongoing element of the TIME program. The committee believes this is a correct approach.

The architecture documents (Raytheon 2000) prepared by the TIME program can be thought of as an important first step in defining, through high-level descriptions—or benchmarks—the advancements that the integrated munitions enterprise will require to bring its capability to a par with commercial enterprises during the next 5 to 10 years. The program additionally makes clear that it intends to update these architectures as the capabilities of commercial systems and enterprises improve.

"Metrics" (typically defined as standards or measures) can serve either as a means to define or describe specific capabilities or as a set of specific defined goals and objectives against which an effort, such as the TIME program, can be measured. The TIME program appears to use detailed metrics primarily as a means to describe the capabilities of segments of proposed enterprise integration tools, as demonstrated under selected conditions (see Chapter 6).

The existing metrics for the TIME program are general and long term in nature. Although the metrics can be used as a means to define visionary concepts, the committee believes that they are of little value as tools to evaluate the progress of the program. These metrics include the following (Burleson 1999b):

- Reductions in replenishment base or overhead,
- Reductions in cycle time and acceleration of the acquisition cycle,
- Reductions in life-cycle costs,
- Success in capturing manufacturing process knowledge, and

- Increasing ability and efficiency in transitioning process knowledge to industry.

The committee believes that, although these are appropriate long-term, visionary goals, the TIME program should develop shorter-range, detailed subsidiary metrics to more precisely measure the progress of TIME. Metrics used by the Army ManTech organization to measure the progress of its projects have been proposed as one set of metrics to be used to measure TIME.

The committee was asked to benchmark the TIME program against the findings of two previous NRC Board on Manufacturing and Engineering Design studies, *Visionary Manufacturing Challenges for 2020* (NRC 1998) and *Defense Manufacturing in 2010 and Beyond* (NRC 1999). The committee believes that this is appropriate because the efforts of the TIME program are intended to result in changes to the munitions industry that will remain in place, with minor upgrades, for decades to come. The committee considered only those recommendations that pertain to the munitions industry.

VISIONARY MANUFACTURING CHALLENGES FOR 2020

The purpose of this section is to assess the goals and accomplishments of the TIME program in relation to the findings of the Visionary Manufacturing study.

The objective of the study was to identify the technical challenges that would be faced by manufacturers in 2020 and the technologies that would be required to enable them to remain productive and profitable. "Manufacturing" was defined in the Visionary Manufacturing report, in broad terms as "the processes and entities required to create, develop, support, and deliver products" (NRC 1998, p. 9).

The Visionary Manufacturing study committee developed a scenario of the environment for manufacturing in 2020 and from it identified six visionary grand challenges that the manufacturing community would need to address to achieve success. The following sections will use these grand challenges as long-term benchmarks against which the goals and accomplishments of the TIME program will be compared.

Grand Challenge 1: Concurrent Manufacturing

This challenge calls for implementation of integrated business systems that enable concurrent conceptualization, design, and production of products and services to reduce time-to-market, encourage innovation, and improve quality. Enterprises practicing concurrent manufacturing will consider product support, including delivery, servicing, and end-of-life disposition (recycling, reuse, demilitarization, or disposal) during the entire life cycle of the product, especially in the design and production phases.

The TIME program has addressed the issue of concurrent manufacturing in its Enterprise Architecture report (Raytheon 2000) that serves as a guideline for execution of the TIME program. The report contains an extensive discussion of the use of integrated product teams. Although the report identifies the integrated product teams as essential, it is not clear from the architecture how they will actually function across multiple contractors with diverse contracts. Furthermore, the TIME committee noticed a lack of consideration for life-cycle costs and environmental concerns as part of the concurrent design and manufacturing process. Presentations to the TIME committee by program representatives outlined a vision in which future munitions manufacturing systems must be totally integrated, encompassing all of the elements of agile manufacturing as well as employing Web-based management of a virtual enterprise structure. There was insufficient detail supporting these concepts to enable an effective evaluation, although as an outline for an integrated munitions enterprise it appears to present a state-of-the-art vision that is similar to those being implemented in today's commercial industry.

Although a good strategy was presented to the committee, a detailed plan for implementing concurrency has yet to be developed by the TIME program. However, it is TIME's intent to use a product realization process model adopted from the work of DoE's Technologies Enabling Agile Manufacturing (TEAM) initiative. It is claimed by the TEAM initiative that the TEAM process and TEAM models force the concurrent definition of product, process, and resource issues and manage their current resolution.

A detailed plan is essential if TIME is to achieve its long-term objectives. It was not made clear to the TIME committee how the projects currently under way will assure or even incorporate concurrency, as communicated by the enterprise architecture. However, a high level of computer-integrated manufacturing is essential. This is addressed conceptually in the architecture. The shop floor control projects associated with TIME are only a small piece of the integrated manufacturing system. The focus of the TIME program may be driven by the large quantity of machine tools in a mothballed state and the difficulty of maintaining their control systems in any state of readiness. Likewise, the architecture document does not disclose a plan for implementing concurrent engineering in the complex, government-driven environment that will exist as contracts are negotiated with commercial firms for replenishment. The committee believes that there should be a strong commitment on the part of the military to implement fundamental changes in its approach to munitions acquisition. Encouraging signs in this regard are found in a June 30, 1998, Industrial Base Policy Letter by Paul J.Hoeper, Assistant Secretary of the Army (Hoeper 1998), which advanced the following:

- Manage ammunition using DoD's life-cycle acquisition process.
- Use acquisition reform initiatives to stabilize the business environment and provide incentives for private investment in the production base.

- Rely on the private sector to create and sustain ammunition production assets in response to production and replenishment contracts.
- To the maximum extent feasible, transition government-owned ammunition production assets to the private sector while preserving the ability to conduct explosives-handling operations safely.

The committee believes that the TIME program should adopt this approach and plan for a virtual, reconfigurable munitions industry that will deeply involve the private sector. The TIME committee saw no evidence that such plans had been formalized or that implementation had begun, and there were no details about which government-owned resources should be transferred into the private sector and what kind of relationships should exist regarding their operation.

The TIME committee believes that concurrency can drastically shorten the time between the conception of a product and its realization. However, there is little evidence in TIME program materials that suggests how these concepts will be applied to munitions manufacture or how they will relate to new weapons deployment. Readiness in the military sense may not directly map onto the concept of concurrency in the same way that it does in bringing new commercial products to market.

Recommendation: As recommended in the Visionary Manufacturing report, the TIME program should adopt concurrency as a central tenet of its plans for upgrading the munitions industry and implement its use throughout the product realization cycle, with appropriate consideration of the full life cycle economic and environmental impacts.

Grand Challenge 2: Integration of Human and Technical Resources

The Visionary Manufacturing study found a compelling need for industries in 2020 to become effective in integrating their advanced technical resources with their workforce. However, the issues surrounding the integration of human and technical resources have barely been addressed by the TIME program. Human resources will be an essential ingredient in a modern munitions industry. It was made evident to the TIME committee that the United States has adequate munitions production capacity, although at present many mothballed systems could not be rapidly deployed because in today's employment market, the necessary employees are simply not available. A process for recruiting and educating an expanded workforce with the proposed technologies, in a short period of time, must be developed and a realization plan put in place. The TIME program and its enterprise architecture appear to assume the ready availability of required human resources.

Recommendation: A human resource plan is needed to parallel the technology plans and enterprise architecture of the TIME program.

The Visionary Manufacturing study also found that teamwork of the future involves interactive computer networks linking workers from all aspects of the business. New social relationships and communication skills will be necessary, as well as new corporate and enterprise cultures in which success will require not only expertise and experience but also the ability to use knowledge quickly and effectively. The TIME program has not addressed this global view of the team environment of 2020. To address this issue, it is necessary to define employee education and skill requirements; methods for developing continuing education programs; software, hardware, and communications system support; and supply chain relationships and requirements. In a general manner, however, the TIME architecture outlines appropriate system requirements. It is also safe to say that many workers in the future will already have extensive computer and modern communications skills when hired.

Recommendation: The committee recommends that the TIME program prepare detailed plans for (1) upgrading the munitions workforce so that it may interface effectively with the proposed technologies of the totally integrated munitions enterprise of the future, and (2) rapidly expanding and training the new workforce in the event of a national emergency.

Grand Challenge 3: Conversion of Information to Knowledge

Like commercial enterprises of 2020, future munitions operations must successfully address two related challenges: (1) capture and storage of large amounts of data and information “instantaneously” and transformation of it into useful knowledge, and (2) making this knowledge available to users (human and machine) “instantaneously” wherever and whenever it is needed in a familiar language and form.

Achieving this challenge identified by the Visionary Manufacturing study assumes that the prior education of the workforce will prepare them to deal with information in new forms and that the data-to-knowledge relationship will be well defined. The TIME program literature implies this to some extent, but it is not clearly defined as part of the project. It does not appear that any specific projects are under way to prepare the munitions enterprise to perform, using up-to-date systems, in this new information-based environment.

The TIME program is correctly assuming that the majority, if not all, of the software for these relationships can be purchased off-the-shelf. However, at present, commercial software falls far short of creating the information sharing and manipulation capabilities suggested by the Visionary Manufacturing report, although extensive commercial sector work is under way in these fields. Furthermore, the TIME enterprise architecture provides few details regarding the required capabilities of the new software that is needed to achieve the architecture of the future as they relate to conversion of information to knowledge. It is the opinion of the committee that the integration of the munitions enterprise and the production of conventional munitions of the types in production today are highly unlikely to require information systems with capabilities beyond those that will be used in the commercial sector. However, as in the commercial sector, it is likely that extensive use of intelligent agents will be required to fully convert large amounts of data into useful knowledge. At a minimum, all participants must have compatible, interoperable software and must participate in a well-planned Internet strategy to achieve concurrency with complex engineering systems.

Finding: The TIME program is focused on the information gathering, conversion, and transfer process but has yet to address the ultimate issues of converting information to knowledge.

Recommendation: The TIME program should develop a plan for establishing a unified central knowledge base for the munitions industry.

Grand Challenge 4: Environmental Compatibility

The Visionary Manufacturing report (NRC 1998) points out that the following must occur to achieve "near zero" production waste and product environmental impact: (1) Manufacturing enterprises must develop cost-effective, competitive products and processes that are produced without harming the environment, and (2) as much recycled material as possible should be used for feedstock and no significant waste created in terms of energy, material, or human resources.

The TIME program does not address issues of past, present, or future environmental problems associated with munitions manufacturing. Passing mention was made in presentations to the TIME committee of achieving near zero waste and "green bullets," however, no supporting detail was provided. Through a recent Executive Order, all future weapon systems must be evaluated to determine their full life-cycle costs and environmental impacts throughout all life-cycle stages, from feedstock production and manufacturing to operations and service and eventual demilitarization. Unfortunately, TIME has not integrated design-for-environment or life-cycle assessment methodologies or tools into any of its program elements.

Recommendation: Issues associated with the environmental impact of the production, storage, demilitarization, disposal, and recycling of munitions should play a key role in the TIME program's long-range plans.

Recommendation: The TIME program should work closely with other DoD programs that are working toward cleaner, greener, safer armed forces and those that address issues of health and safety.

Grand Challenge 5: Reconfigurable Enterprises

The Visionary Manufacturing study identified the need for rapid reconfiguration of manufacturing operations and stressed the importance of being able to rapidly form and modify complex business alliances in the rapidly changing manufacturing environment of the early 21st century. This challenge suggests new organizational concepts including the following:

- Intraorganizational and interorganizational structures based on flexible, transient cooperation models,
- Focus on opportunity-specific enterprises rather than on self-preservation and growth,
- Sharing of information and technology among competitors, and
- Resolution of issues related to worldwide patents and equitable sharing of the rewards of collaboration and other intellectual property rights.

The TIME enterprise architecture identifies elaborate structural relationships between the constituent participants in the munitions design and manufacturing enterprises. The proposed models are traditional, published concepts that have been used in many businesses. What is needed is a vision for the future as to how these enterprises may be reconfigured in a rapidly changing environment, as may occur under replenishment conditions. For example, the current labor market has created near zero unemployment. How will a sudden demand for munitions replenishment be met in a short period of time should national defense demand such a response? TIME needs to address many such questions relative to the proposed virtual enterprise. In some presentations, the TIME program made a major point of the need to develop a “reconfigurable,” virtual enterprise but provided no details regarding how this will be achieved. Detailed business relationship models have yet to be developed. In addition, TIME has encountered difficulties in early demonstration projects with regard to intellectual property rights and technology transfer. These issues must be successfully addressed prior to or early in the implementation phase.

Recommendation: The TIME program should develop appropriate detailed plans that will enable rapid reconfiguration of the munitions industry as needed to meet changing national priorities.

Grand Challenge 6: Innovative Processes

This challenge outlines the need to develop innovative manufacturing processes and products with a principal focus on decreasing volumes of increasingly customized products and decreasing dimensional scale. The challenge is to apply totally new concepts to manufacturing unit operations, which will enable dramatic changes in production capabilities. The design and development of defense systems has for decades focused on the theme of decreasing dimensional scale. Many of the developments in microelectronics had their origins in defense research and development. The focus of the TIME program on agile manufacturing will address issues relating to short runs of semicustom munitions. However, TIME has yet to address the need to explore manufacturing at decreased dimensional scale.

Advanced energetics, smart weapons technology and innovative warhead and submunitions designs are likely to combine in a trend toward smaller volumes of semicustom, high-performance, and, in some cases, miniaturized munitions and submunitions. Although the committee is of the opinion that most, if not all, of the new munitions should be produced by private industry, history would indicate that the entire conventional munitions industry, as addressed by this study, should prepare itself in anticipation of an eventual role in the production of these advanced weapons. Clearly, innovative, flexible processes and process modeling and control will be essential for future munitions manufacturing and should be addressed.

The Visionary Manufacturing report suggests that manufacturing operations during the next 20 years will likely need to become proficient in the following:

- Development of “designer materials” by varying material composition throughout fabrication, joining, and assembly operations. These materials could create demand for some aspect of reconfigurable munitions manufacturing systems.
- Creation of self-directed processes that will simplify tooling and programming requirements and provide greater operational flexibility. This has not been addressed by TIME other than through work on the open modular architecture controller (OMAC).
- Manipulation at the molecular or atomic level that will lead to the creation of new materials and may eliminate some separate parts. This issue has not been addressed by the TIME program, as there are no identified needs in the munitions industry of which the TIME committee is aware. However, if research work on nanostructured energetics, which attempts to optimize material performance on a scale slightly higher than the molecular level, is successful, the TIME program must be prepared to efficiently address the realization of munitions containing these advanced materials.

Recommendation: Research efforts in the field of nanoenergetics may yield practical results in the near future. The TIME program should actively involve itself in efforts to realize products using these technologies and should strongly consider using these projects as opportunities for the implementation and measurable demonstration of integrated enterprise technologies.

Nine technology areas were identified in the Visionary Manufacturing report as the most important for meeting the grand challenges:

1. *Adaptable, integrated equipment, processes, and systems that can be readily reconfigured*. These technologies are correctly viewed as critical by the TIME program. However, TIME must begin by conducting assessments of current processes to evaluate what is obsolete, what is fundamental and can be changed, and what should be discarded in lieu of supplier dependency through new supply chain relationships.
2. *Manufacturing processes that minimize waste and energy consumption*. This is becoming increasingly important for munitions manufacturing, but TIME has yet to address these subjects with detailed plans and guidelines.
3. *Innovative processes for designing and manufacturing new materials and components*. These will be of critical importance with the increased use of electronics for precision-guided munitions and the potential for advanced energetics. Although lacking details, the TIME program has prepared an architecture for product realization that compares favorably with state-of-the-art approaches of commercial U.S. industry.
4. *System synthesis, modeling, and simulation for all manufacturing operations*. These will be critical for upgrading munitions development and manufacturing capabilities. To date, the TIME program has addressed these topics only in general terms. Significant benefits can accrue to the Army if modeling and simulation tools used in research laboratories for development and validation of initial materials concepts can be made interoperable with computer-aided design (CAD) and computer-aided manufacturing (CAM) tools required for detailed design, and process development and control.
5. *Technologies to convert information into knowledge for effective decision making*. These technologies, including intelligent agents, are exhibiting improved performance and are gradually becoming commercially available. They will be critical for effective operation of the integrated munitions enterprise. The TIME program has yet to address these issues.

6. *Product and process design methods that address a broad range of product requirements.* These technologies, including advanced CAD, and modeling and simulation programs that run on high-performance computers are increasingly being used by designers of munitions and advanced energetics. They are essential to achieve an effective munitions enterprise and are being addressed by the TIME program as part of their product realization architecture.
7. *Enhanced human-machine interfaces*. This topic was not discussed in presentations by the TIME program, but it will be an important part of the integrated munitions enterprise.
8. *New educational and training methods that enable the rapid assimilation of knowledge*. This topic was briefly mentioned in TIME presentations. It must be a focal point if the U.S. integrated munitions enterprise is to succeed in the current employment marketplace and if the U.S. replenishment capabilities are to perform effectively when called upon.
9. *Software for intelligent collaboration systems*. This software will be essential for TIME, but it is not commercially available to meet industry needs. This lack of current availability should not inhibit TIME program efforts to begin implementation of the integrated enterprise, and the Army should not invest in development of this software. The committee predicts that commercial developers will have validated packages available by the time the munitions industry is ready to implement them.

Summary

Manufacturing in 2020 will be exciting, dynamic, and competitive. The military must take advantage of this environment on behalf of the U.S. taxpayer. TIME has the potential for setting the U.S. munitions enterprise on a new course, although to date many issues remain to be defined and addressed regarding how the transition will or could occur.

The Visionary Manufacturing study was intended to look two decades into the future. The TIME program is doing such now, and it appears evident to the committee that there is a national need to apply serious effort and resources to begin to resolve the problems facing the U.S. munitions enterprise. Given severe budgetary constraints, the TIME program cannot be expected to be immediately and fully responsive to all of the challenges posed in the Visionary Manufacturing study. However, the committee believes that it is essential that the TIME program seriously address each of the six grand challenges. Concurrent manufacturing, integration of human and technical resources, conversion of information to knowledge, environmental compatibility, reconfigurable enterprises, and innovative processes should be thought of as cornerstones for TIME program success. The TIME program staff must maintain an in-depth, up-to-date understanding of the rapidly evolving commercial tools and concepts in all of these six areas, so that the TIME program can support and enable the rapid introduction and integration of these technologies as needed by the munitions industry.

One of the grand research challenges identified in the Visionary Manufacturing study (NRC 1998) was to “integrate human and technical resources to enhance workforce performance and satisfaction.” The report stated, “Individuals and teams will have to be agile to maintain control over time and technology, and to capitalize on both.” Agility in teams and individuals is accomplished by extensive cross-training and rapid learning throughout the enterprise, thus allowing for the rapid assimilation of new technologies. The report concluded that “enterprises that can teach workers new skills quickly will have a competitive edge.”

In the munitions industry, the emphasis is on readiness instead of competitiveness, but the means to achieve both are, for all practical purposes, the same. The organization must assess its training and skills needs; the readiness state must be monitored continuously; and the impact of any changes in workforce or training needs must be determined, communicated, and corrected as quickly and automatically as possible. The TIME program does not have formal programs identified, established, or planned in any of these important areas. It must work closely with other DoD programs to coordinate efforts to assure that appropriate skills can be made available as needed in response to national needs that can change rapidly. However, many of the skills required for replenishment will be resident in the workers who, in normal times, will be using the dual-use equipment to make commercial parts.

DEFENSE MANUFACTURING IN 2010 AND BEYOND

The findings, challenges, and recommendations of the Defense Manufacturing study (NRC 1999) are found in the Executive Summary of that report. The portions of the study that are appropriate as benchmarks for the TIME initiative are found under the headings “Required Defense Manufacturing Capabilities” and “Advances in Commercial Manufacturing.” Other portions of the report are directed at DoD and ManTech, not at specific initiatives such as TIME.

The two sections of the Defense Manufacturing report selected as benchmarks include those technical and organizational capabilities and commercial advances that TIME program managers are in a position to pursue or acquire if they so choose.

Required Manufacturing Capabilities

The Defense Manufacturing study identified six broad categories of defense manufacturing capabilities that are defense unique or defense critical:

1. Composites processing and repair;
2. Electronics processes;
3. Information technology systems;
4. Weapons system sustainment;
5. Design, modeling, and simulation; and
6. Production processes.

Detailed elements under each of these categories are listed in Table 2–2 of the Defense Manufacturing report (NRC 1999) and are reproduced here as Table 7–1 for easy reference. The sections that follow provide discussion of these defense manufacturing capabilities within the context of the TIME program.

Composites Processing and Repair

Although "composite materials" is listed as a technology area in the TIME presentation materials (McWilliams 1999), the program has not yet addressed composites. The initial phases of TIME instead focus on metal parts; energetics (propellants, explosives and pyrotechnics); load-assemble-pack; fuses; and submunitions (Osiecki 1999), the traditional categories of conventional munitions making. It is increasingly likely, however, that new munitions designs will take advantage of the performance opportunities available from advanced composites. Thus, the committee feels that it is appropriate to benchmark the approaches of the TIME program against the recommendations regarding composites processing and repair.

Electronics Processes

Although the early phases of the TIME program are focusing on the product realization environment of mechanical piece parts, the TIME master plan includes the development of a product realization process for electronic parts and assemblies, which are of increasing importance for smart munitions. The Defense Manufacturing report identified numerous specific advancements needed in electronics processing, whereas TIME will correctly be concerned with a more generic product realization environment for munitions manufacturing and sustainment. In the opinion of the committee, if all of TIME's stated objectives are eventually achieved, the resulting product realization environment would facilitate the attainment of the specific advances in electronic processes identified in the Defense Manufacturing report.

Information Technology Systems

The recommended manufacturing requirements for information technology systems are presented below, along with discussion of how the TIME program has addressed each requirement.

TABLE 7–1 Broad Categories of Required Defense Manufacturing Capabilities

Category	Manufacturing Capabilities
Composites processing and repair	Design methods and processes for low-cost structural composites Design methods for low-cost composite materials Composite materials for advanced propulsion systems Low-cost composite surfaces for tactical missiles Automated composite repairs On-system, on-site composite repair technologies that are affordable and efficient
Electronics processes	Intelligent health monitoring systems Electronic systems able to withstand high *g* loads and severe vibration environments High-density packaging for functional elements using monolithic microwave integrated circuits Electronics packaging with increased structural reliability Built-in test diagnostics Commercial programmable network protocols to replace existing buses and networks Software engineering tools to facilitate upgrades Lightweight chip-on-board technology for miniaturization High-precision, high-reliability connectors, back planes, and traces Interruption-free connector systems Optical interconnections for ultra-high data rates Designs to prevent dendritic growth in high-density electronics Manufacturing technology for liquid crystal displays
Information technology systems	Commercial software systems to replace proprietary systems Systems architecture that permits secure use of commercial off-the-shelf computers, software, and networks Defense logistics systems that are interoperable with the diverse systems used by suppliers Network management and control protocols to ensure data security in distributed design and manufacturing operations Databases containing weapons systems life-cycle costs for integration into design systems Production process capabilities and cost databases for integration into design systems Product data models and storage and retrieval architectures capable of handling data seamlessly Product structure directories that are open and meet commercial standards Intelligent agents for locating and retrieving information Automated reverse-engineering systems based on scanning of the actual part

Information technology systems	Nonrecurring manufacturing process control with single view management, single numbering system, and visual statusing system
Sustainment	Repair techniques for aging systems Nonintrusive, real-time monitoring techniques for flight loads and damage Maintenance and upgrade technologies for aging systems Automated validation tools to replace flight testing Avionics packaging with increased structural reliability and reduced connector problems for aging systems Built-in-test diagnostics for aging systems Modular components to facilitate maintenance of aging systems Software engineering tools to facilitate upgrades
Design, modeling, and simulation	Product models that enable accurate life-cycle performance versus cost trade-offs Integrated product and process development Virtual prototyping System designs based on common subsystems Process simulations based on finite-element analysis of materials characteristics during forming Product models that enable stealth versus other performance characteristics trade-offs Designs for affordable, high-performance radomes and infrared windows Designs for affordable, easy-to-install electro-optical systems with minimum drag and signature Product models with multiple levels of resolution to enable simulation-based designs Parametric modeling to enable design trade-offs Integrated product, tool, and manufacturing process designs Design methods that incorporate tolerance stack-ups Computer-aided design systems that integrate design, production processes, measurement processes
Production processes	Affordable processing methods for launch equipment with reduced drag and signature High-yield, robust fuse production process Methods for precise filling of explosives in munitions Automated filling of explosives in munitions to increase safety, improve process yield, and ensure performance Methods to reduce cycle time and nonrecurring costs in production processes Precise, automated methods for applying low observability coatings Affordable manufacturing techniques, processes, and tools that can form complex shapes Conformal mold line technology Manufacturing processes for multilayer boards

Production processes	Conformal coating techniques to prevent dendritic growth
	Glass manufacturing technology for liquid crystal displays
	Flexible production lines Adaptive process controls to enable 100 percent first-time yields
	Manufacturing processes and assembly sequences that determine tolerance stack-ups for modular construction
	Measurement systems that provide highly accurate electronic information on as-built parts
	Computer-aided visualization techniques
	Noncontact inspection during manufacturing operations
	Automated system for accurate location of assembly tools and components
	Nondestructive inspection for inclusions in titanium castings
	Process for producing titanium 15–3 honeycomb

Source: NRC 1999.

- *Commercial software systems to replace proprietary systems*. The TIME program has expressed a strong preference for use of COTS software and has stated clearly that it will develop its own software only to the extent that enterprise needs cannot be served using commercial software. However, the TIME program has yet to clearly define the details of enterprise needs and standards.
- *Systems architecture that permits secure use of commercial off-the-shelf computers, software, and networks, and network management and control protocols to ensure data security in distributed design and manufacturing operations*. The TIME program is beginning to address the issues of computer security and “need-to-know,” using COTS hardware, software, and networks wherever possible. LCMS (1999) addresses this issue to a limited degree, but substantial additional work appears to be required to define munitions industry needs and systems requirements.
- *Defense logistics systems that are interoperable with the diverse systems used by suppliers*. TIME appears to recognize only generally the importance of developing this capability. Many difficulties will have to be overcome. More TIME program emphasis should be directed toward achieving this capability, as recommended by the committee in Chapter 3.
- *Databases containing weapons systems life-cycle costs for integration into design systems*. The TIME program intends to create and implement database and networking capabilities that will enable weapons system integrated design teams to access a wide variety of design-related information including, potentially, the life-cycle cost history of previous weapons systems.

- *Production process capabilities and cost databases for integration into design systems*. The TIME program is striving to develop and implement database and networking capabilities that will enable distributed concurrent engineering teams (design, process development, etc.) to access in real time huge amounts of design, process, cost, and production data as needed for analysis and design decision making.
- *Product data models and storage and retrieval architectures capable of handling data seamlessly*. TIME clearly recognizes the importance of this capability, and the enterprise architecture outlines, at a high level, a means for achieving it. There are several product data management (PDM) systems available in the market today, and TIME recognizes the need to use commercial systems. However, little information was presented regarding the nature of the data that the TIME program will be trying to model, store, and retrieve. Selection of a PDM system is complex and is based on the problem that needs to be solved. PDM systems tend to be time consuming, costly, and difficult to implement and maintain. It will be hard to implement a PDM system within the scope of the entire integrated munitions enterprise.
- *Product structure directories that are open and meet commercial standards*. Product design definition utilizes several different file formats within which a product directory structure is created. The product directory structure refers to assemblies, components, design and manufacturing features, geometry and process information, all stored in an associative network. Such a structure can be stored in a Standard for the Exchange of Product model Data (STEP) file format. The TIME program is investigating the use of STEP to enable exchange of product data with its suppliers. However, it should be pointed out that, short of using the same CAD/PDM systems that suppliers use, there is currently no seamless solution to data exchange.
- *Intelligent agents for locating and retrieving information*. “Intelligent agents” are mentioned in TIME, but no details are provided. The capabilities of intelligent agents are increasing rapidly and appropriate commercially available and proven software should be employed by TIME as it becomes available. When currently available agents are used to locate and retrieve information, the capability to develop information from historical situations, activities, and subject areas needs to be well demonstrated. Changes in terminology and methods may create difficulties in reprogramming currently used software to perform agency successfully.
- *Automated reverse-engineering systems based on scanning of the actual part*. This capability is not mentioned in the TIME program description.
- *Nonrecurring manufacturing process control with single view management, single numbering system, and visual statusing system*—Parts of the TIME program description are directed to parts

of this capability but only in a general way. TIME should employ commercially available and proven systems for this aspect of its overall architecture.

Sustainment

In general, the manufacturing capabilities required for sustainment of weapon systems are as follows:

- Application of advanced production processes and practices to maintenance, repair, and upgrade operation;
- Technology insertion for new and existing systems;
- Self-diagnostics for mechanical and electronic systems;
- New technologies for remanufacturing; and
- Design methods that improve sustainment.

Although integration of the munitions industrial base will enable more cost-effective sustainment of finished products, TIME has not explicitly considered sustainment issues. However, the program anticipates working closely with managers of the various munitions programs during the product life cycle. Due to the high cost impact, serious consideration should be given to making the above sustainment practices a high priority in the TIME program's work with these individual munitions programs.

Design, Modeling, and Simulation

Manufacturing capabilities for design, modeling, and simulation are discussed below:

- *Product models that enable accurate life-cycle performance versus cost trade-offs*. The TIME program intends to implement systems that facilitate and enable "design optimization," including access to life-cycle cost databases that will enable trade-offs such as performance versus life-cycle costs.
- *Integrated product and process development*. TIME places heavy emphasis on concurrent engineering and integrated product and process development, as detailed in Raytheon (1999).
- *Virtual prototyping*. Virtual prototyping refers to a broad array of activities, including collision detection within assemblies, interference detection, visual mockups, animation, and so on. TIME intends to incorporate this feature, as described in Raytheon (2000) and in Chapter 4 of this report.
- *System designs based on common subsystems*. TIME incorporates this capability.

- *Process simulations based on finite-element analysis of materials characteristics during forming*. TIME intends to incorporate this capability. Commercially available software should be used for this purpose.
- *Product models with multiple levels of resolution to enable simulation-based designs*. This is an important capability, which should be made more explicit and prominent in the TIME initiative. This capability is available in commercial software. TIME needs to focus on the selection and implementation of COTS CAD systems that can be made interoperable with the advanced modeling and simulation systems being used to develop advanced munitions concepts at the research laboratories of the armed forces.
- *Parametric modeling to enable design trade-offs*. Parametric modeling is an activity that is part of today's commercial CAD systems. This capability is available to the TIME program through use of a commercial system, so TIME will incorporate this capability. Design trade-offs follow naturally from using parametric modeling.
- *Integrated product, tool, and manufacturing process designs*. TIME has prepared an integrated architecture that will incorporate this capability.
- *Design methods that incorporate tolerance stack-ups*. TIME incorporates this capability.
- *Computer-aided design systems that integrate design, production processes, measurement processes*. The TIME program's approach to enabling integrated design teams performing concurrent engineering will appropriately address this requirement. In particular, the Design Cockpit and Web Integration Manager (WIM) support this capability.

Production Processes

Production-process manufacturing capabilities are presented below:

- *High-yield, robust fuse production process*. Although not an explicit program element, the successful attainment of the objectives of the TIME initiative will contribute to the achievement of this capability.
- *Methods for precise filling of explosives in munitions*. The enhanced product realization process integral to the TIME initiative would contribute to the achievement of this capability. One of the TIME demonstration projects is directed to this issue.
- *Automated filling of explosives to increase safety, improve process yields, and ensure performance*. The enhanced product realization process integral to the TIME initiative would contribute to the achievement of this capability. One of the TIME demonstration projects is directed to this issue.

- *Methods to reduce cycle time and nonrecurring costs in production processes*. Much of the TIME initiative is directed toward this issue, with more emphasis placed on reducing cycle time than nonrecurring costs.
- *Affordable manufacturing techniques, processes, and tools that can form complex shapes*. Although typically not required in the munitions industry and not an explicit goal of the TIME initiative, the enhanced product realization process integral to the TIME initiative would contribute to the achievement of this capability.
- *Flexible production lines*. This will be increasingly important if trends toward short runs of semicustom designer munitions and smart munitions continue. A key component of TIME is the employment of commercial dual-use facilities for munitions stock replenishment.
- *Adaptive process controls* to enable 100 percent first-time yields. *This is a key goal of the TIME program.*
- *Manufacturing processes and assembly sequences* that determine tolerance stack-ups for modular construction. Although not explicitly mentioned, TIME program efforts to enable and support concurrent engineering should make this readily attainable.
- *Measurement systems that provide highly accurate electronic information on as-built parts*. This capability is not highlighted in TIME materials, but it should be an integral part of the enhanced product realization environment being developed. The real-time networking capabilities that are envisioned by TIME will make this data very valuable to product realization teams.
- *Computer-aided visualization techniques*. This is an integral component of TIME. The plan includes three-dimensional CAD systems and visualization packages, the “design cockpit” concept, and WIM.
- *Noncontact inspection during manufacturing operations*. The TIME program is establishing networking links that can be used to make noncontact inspection data available in real time to all participants. This capability is perhaps not applicable to all aspects of munitions manufacture but is critical in certain areas.
- *Automated system for accurate location of assembly tools and components*. Although not explicitly mentioned in TIME program materials, the committee anticipates that this will be part of the machine control capabilities.

Advances in Commercial Manufacturing

The Defense Manufacturing study (NRC 1999) identified several recent advances in commercial manufacturing that have potential for benefiting defense manufacturing. These are listed on page 2 of the Executive Summary of that report. These advances and an assessment of TIME’s corresponding program elements are summarized below.

- *Advanced approaches to manufacturing accounting, including activity-based accounting and cost-as-an-independent-variable accounting*. TIME does not select the accounting methods but rather provides technologies that can enable communication between systems, standardized databases, and real-time access for those with a need-to-know.
- *Advanced approaches to product design, including life-cycle design, integrated product and process development, three-dimensional digital product models, simulation and modeling, and rapid prototyping*. All of these approaches are integral parts of the TIME product realization architecture. Hardware and software systems are commercially available that are quite adequate for most munitions industry needs. The Army is already using three-dimensional modeling and simulation techniques on high-performance computers to develop concepts for advanced munitions. TIME should focus on the implementation of interoperable COTS CAD/CAM/CAE systems to seamlessly create product and process design documentation from the high-performance models. Rapid prototyping, as needed, can probably be performed most cost-effectively through contract rapid prototyping services.
- *Advanced approaches to manufacturing processes, including generative numerical control, adaptive machine control, predictive process control, high-speed machining, flexible tooling, soft tooling, tool-less assembly, and nanotechnology*. Some of these advances are outside the scope of TIME. TIME should continue to focus its efforts on enterprise integration but must work closely with other DoD efforts to upgrade munitions manufacturing processes. For example, COTS tools and technologies, as already defined by the TIME program, should be implemented to enable faster realization by the Army of advanced energetics involving nanotechnologies.
- *Advanced approaches to business organization, including teaming across organizations, virtual enterprises, long-term supplier relationships, high-performance organizations, cross-functional teams, lean enterprises, adaptive enterprises, agile enterprises, and knowledge-based and learning enterprises*. Many of these issues are being appropriately addressed as key pieces of the TIME program. However, the plan does little to address some of the issues, particularly those involving people. Efforts to date have focused primarily on high-level architectures, design capture and translation, and machine tool controllers.
- *Information and communications technologies, including electronic commerce, virtual collocation of people, data interchange standards, internet technologies, intranet technologies, browser technologies, intelligent agents, seamless data environments, telecommunications, and distance learning*. TIME places great emphasis on these issues. Most of these specific technologies are undergoing rapid development

and change, and these changes will continue for a long time. The TIME program materials reviewed were somewhat lacking in specifics of the program's overall approach to these technologies, strategies for making selections, and means for staying current with commercial developments. The TIME program plans to incorporate available Web-based tools. These tools will undergo substantial change over the next few years. The TIME program should devote additional effort to define the needs of the munitions industry in detail, to translate those needs into detailed specifications for COTS information and communications technologies, and then begin implementation based on well-defined priorities. It is advisable that acquisition and integration of tools be part of a larger strategy because integration of such tools can consume substantial resources.

Summary and Recommendations

The NRC study *Defense Manufacturing in 2010 and Beyond* (NRC 1999) was a broad, high-level analysis of the overall U.S. defense industrial base. While the study included munitions manufacturing, the conclusions and recommendations were quite general. Nevertheless, the TIME program can benefit by using appropriate elements of this study as a frame of reference.

Overall, the TIME program measures reasonably well against the key recommendations of the Defense Manufacturing study. Major areas in which TIME should increase its efforts are as follows:

- *Electronic component manufacturing*. TIME has intentionally focused its early efforts on mechanical piece parts and intends to address electronics manufacturing in a later phase. It is important to accelerate this portion of the program in order to respond to the challenges faced in producing ever-more-sophisticated munitions.
- *Information technology systems*. The TIME program should place much more emphasis and devote a larger share of its budget to this critically important area. While some progress has been made (e.g., design cockpits and WIM), TIME should make greater use of commercially available information technology. Strong capability should be developed in the areas of Internet communications, e-commerce, and supply chain integration.
- *Design, modeling, and simulation*. TIME recognizes the importance of this area, but its overall emphasis on this capability is perceived by the committee to be inadequate, including a lack of consideration of product life-cycle costs and environmental impacts. Special emphasis should be placed on enlarging and upgrading munitions industry technical personnel in this critically important area.
- *Production processes*. The committee believes that TIME has erred in focusing so much of its attention and resources on the OMAC. TIME should be increasing its capability to implement and manage

commercially available CAD/CAE/CAM systems, controllers, and networks. It should also begin to prioritize the acquisition of production equipment and processes that are capable of producing high-quality munitions.

- *Consideration of the human element*. The TIME program should pay increased attention to the importance of the workforce. It mentions training but does not have an action item directed to this need. The human element issues in advanced manufacturing systems and replenishment are much broader than just training.
- *Enterprise business systems*. The TIME program has begun to define (at a high level), and demonstrate examples of, an “enterprise systems toolkit.” It is critically important that TIME develop a strong capability in this area and that of supply chain management and that the program be given sufficient funding to prioritize and begin to implement appropriate commercial systems.

A WORD OF CAUTION

The two previous NRC *studies—Defense Manufacturing in 2010 and Beyond* (NRC 1999) and *Visionary Manufacturing Challenges for 2020* (NRC 1998)—were intentionally conceptual and futuristic, containing considerable speculation regarding possible advances in manufacturing processes, systems, and enterprises over the next 10 to 20 years. Some of the advances visualized in these reports may never materialize. Others may materialize but at a slower pace. Still others may prove to be impractical or not cost-effective.

The committee adds these cautionary comments because it believes strongly that the Army should not attempt to reach too far, too fast, in its efforts to modernize its munitions manufacturing capability. In many cases, munitions manufacturing is several decades behind current commercial practices and today’s COTS technologies can offer substantial improvements in many areas. With careful prioritization of needs and potential returns, significant improvements can be made to the capabilities of the industry with a relatively modest, though significantly increased, budget. It would be expensive and potentially risky for the Army’s munitions facilities to attempt to leapfrog from their current state of technological immaturity to the futuristic environment described in these two NRC studies. Consequently, while these studies can serve as general visions of desired long-term objectives, they should not serve as realistic near-term targets. It is important that the TIME program update its architectures, goals, and metrics on a regular basis, benchmarking them against evolving COTS capabilities, commercial best practices, and these visionary reports, to guide the munitions industry toward meeting military needs with an appropriate level of taxpayer investment.

8

Conclusions and Recommendations

MUNITIONS MANUFACTURING POLICY

The Department of Defense's (DoD's) current replenishment policy stipulates that (1) the munitions stockpile must meet peacetime needs, (2) The munitions stockpile must support two near-simultaneous major regional conflicts, and (3) the munitions manufacturing base must be capable of replenishing the stockpile within 3 years. The policy assumes that the organic munitions base will meet peacetime needs and that a large portion of stockpile replenishment following conflicts will be performed by commercial firms that are under contract to operate dual-use facilities with munitions manufacturing capability. In the event that stockpiles are severely depleted, it is assumed that the "cold base" can be reactivated quickly for munitions production.

Conclusion: The concept of idling factories full of precision machines and laying off highly skilled people, often in munitions-specific fields, with the expectation of quick startup at an unknown time in the future makes the creation of a truly effective replenishment strategy extremely challenging.

Conclusion: Based on briefings and documents available to the committee, many of the Army's munitions manufacturing facilities are obsolete.

MUNITIONS INDUSTRY CAPABILITIES

Modernization of Munitions Industrial Base

Several previous studies (GAO 1996b; PNNL 1997; NDU 1996, 1997, 1998) have documented in detail the current state of the U.S. munitions industrial base. Major problems identified in this and previous studies are:

- Extensive obsolescence of manufacturing equipment and processes,
- Problems in the quality control of processes,
- Scarcity of machine tool numerical controllers,

- Legacy of a sequential (as opposed to concurrent) product realization framework,
- Lack of use of information technology,
- Lack of modern skills and knowledge among the workforce,
- Huge overheads associated with idle and underutilized facilities,
- Lack of a modern supply chain concept for the munitions enterprise,
- Lack of in-house technological experts in modern manufacturing techniques and database management, and
- Need to sustain critical technologies and skill sets that are not likely to have self-supporting commercial uses.

Conclusion: The Army has not followed the accepted commercial business practice of investing continuously to keep its munitions manufacturing infrastructure (facilities, equipment, and workforce) reasonably up-to-date.

The problems addressed by the Totally Integrated Munitions Enterprise (TIME) program are real and the munitions industry needs to change to address them. There are tremendous opportunities through application of modern commercial business practices and commercial-off-the shelf (COTS) technologies to reduce costs in the munitions industry while substantially improving its responsiveness to the nation's needs. The DoD must provide clear overall guidance to ManTech and the TIME program in this regard. Strong leadership from the Army ManTech program office is required to create a unified plan for addressing the near-term and long-term needs of the munitions industry, as well as detailed, short-term plans for developing and implementing technologies, agreements, workforce training, and other actions to address the most pressing near-term needs.

The committee has concluded that the U.S. munitions enterprise needs to undergo a thorough modernization of its organic base. The committee's recommendations follow logically from this conclusion. The committee recognizes that Congress and DoD are faced with a complex challenge. Factors contributing to this complexity include the following:

- A period of limited perceived conventional warfare threat to U.S. interests but increasing threats of terrorism and regional conflicts,
- A large stockpile of increasingly obsolete conventional munitions that is expensive to maintain and manage,
- Tight budget limitations within DoD, and
- Advances in electronics and the possibility that revolutionary improvements in energetics may make a large portion of our conventional weapons obsolete.

In view of these factors, it is difficult to determine the level of resources that should be directed toward modernizing conventional "dumb" munitions facilities. However, with smart munitions playing an ever more prominent role in U.S. defense capabilities, the committee believes that it is essential that the industry segments producing smart munitions be kept thoroughly up-to-date with proven COTS technologies.

While the committee recognizes that important differences exist between commercial and defense manufacturing requirements, the urgency for modernization of munitions manufacturing to at least the current level of commercial practice in a time of cost containment offers no course other than adoption and adaptation of COTS technology.

Conclusion: The committee agrees with DoD’s strategy for achieving greater efficiency in munitions procurement, as stipulated in a policy letter from the Honorable Paul J.Hoeper, Assistant Secretary of the Army (Hoeper 1998b). The major elements of the strategy are as follows: (1) manage ammunition using DoD’s life-cycle acquisition process, (2) use acquisition reform initiatives to stabilize the business environment and provide incentives for private investment in the production base, and (3) rely on the private sector to create and sustain ammunition production assets in response to production and replenishment contracts.

The letter also states that the Army should, to the maximum extent feasible, transition government-owned ammunition production assets to the private sector while preserving the ability to conduct explosives handling operations safely.

Private Sector Production

Recommendation: The committee recommends that the Army transfer production requirements to the private sector wherever possible, thereby limiting the resources needed to upgrade or replace production equipment and systems in government-owned/government-operated (GOGO) facilities that have become obsolete. If needed in case of conflict, modernization of the required GOGO facilities will offer substantial payback to taxpayers in responsiveness, cost savings, and ability to transition new generation munitions to production.

Recommendation: For those requirements that must remain in the organic (GOGO) base, the Army should upgrade its production equipment and processes to make them compatible with those currently used by commercial industry, so that outsourcing for stockpile replenishment becomes a viable option. This will require modification of many production processes.

TECHNICAL AND PROGRAM APPROACHES

Given the relatively primitive state of munitions acquisition, manufacturing, replenishment capabilities, and product realization and the severely limited defense budgets available for modernization of the munitions industry, the TIME program, in general, cannot and should not be a leader in manufacturing technology. Commercial industry is moving rapidly to develop effective tools to meet most of the needs of the TIME program. Technology gaps will appear primarily as they relate to military-specific TIME requirements; the committee saw no such gaps. It is in the gaps that TIME will need to make a technological contribution. It is important for TIME to work continuously to identify and resolve military-specific technology gaps when and if they are discerned.

Conclusion: The key element from a strategic point-of-view is integrated design and manufacturing. TIME should balance its emphasis between shop floor activities and the design environment.

Modernizing the munitions industry presents a complex problem that includes a combination of management, political, economic, and cultural (i.e., people) issues, not just technical issues. Yet, the TIME program was set up to focus almost exclusively on the technical aspects of the problem.

An integrated, multifaceted approach is required to address the problems of the munitions industrial base successfully and cost-effectively. Therefore, the scope and funding of TIME should be expanded to meet this compelling national need.

The committee recognizes that the perceived need for munitions manufacturing capabilities changes with evolving perceptions of threats to the security of the United States. The committee also recognizes limitations in the defense budget for conventional munitions and the advantages of postponing implementation of modern enterprise integration technologies if conventional munitions capabilities may not be called upon in the foreseeable future. However, the committee also believes that it is important to recognize the low levels of investment in the munitions industry in the past several decades, the challenges and length of time required to implement many of these changes, and the substantial benefits that have accrued to commercial industries from their investments in these capabilities. Commercial industries, in many cases, have found themselves at the “bleeding edge” of many of these technologies, expended great effort to get them debugged, and found cost-effective ways to implement them. This process is likely to continue in the future, with great potential benefit to the munitions industry and the taxpayer from this substantial investment by commercial industries.

Recommendation: The Army should follow the practice of acquiring state-of-the-market, commercially available technologies whenever possible. It should not engage in developing technologies, with the possible exception of specific technologies clearly determined to be DoD-unique, urgently needed, and lying on the critical path toward modernization.

Recommendation: As part of its upgrade, TIME needs to develop a long-term strategic plan that conforms with DoD plans and munitions industry needs and that clearly shows ownership, responsibility, and accountability. The TIME program needs to reset its direction and objectives by taking a bottom-up analysis approach to both new product introduction and replenishment capacity management. It then needs to develop a short-term implementation plan with measurable goals and objectives. Furthermore, it should do the following:

- Establish a clear statement of vision, mission, and goals and communicate this information throughout the Department of the Army.
- Tie the responsibility of each organization and participant to the realization of that vision and establish a leadership structure to make the vision come alive.
- Continue the process of benchmarking against commercial industry. This is a moving target. Potential showstoppers today may be solved by commercial industry tomorrow.
- Continue the process of demonstration projects for the transfer of technological capability and incorporate a long-term plan to reach specific goals.
- Implement CAD/CAM/CAE systems and appropriate employee training. Ensure that the designs and manufacturing processes for all munitions are implemented in computer-aided design/computer-aided manufacturing/computer-aided engineering (CAD/CAM/CAE).
- Prioritize needs and opportunities in conformance with the architecture and begin to implement the pieces with the highest paybacks.

Recommendation: In accordance with the architecture proposed by TIME, the entire acquisition process for munitions, from ordering to payment, should be automated and integrated into one loosely coupled, unified enterprise system. This includes the processes utilized by the entire munitions supply chain. Largely, the COTS technology to achieve this vision is available today. TIME is correctly focusing on the overarching framework for integrating the various elements of the product realization process into an enterprise system using today's COTS technology. What remains to be developed are the process of integration, the infrastructure, and the rules governing that process.

Conclusion: The committee believes that the TIME program is developing an approach to an integrated enterprise that may offer potential for other DoD manufacturing enterprises.

TIME is correctly planning to regularly reassess the technological framework that it is using to meet its goals and to update its framework relative to the realities and opportunities of changing industry norms and evolving national priorities. In other words, TIME should correctly be viewed not as a final destination but rather as a journey.

Recommendation: DoD, through the TIME program, should carefully and thoroughly analyze the opportunities for cost and inventory reduction that may be available through utilization of proven commercial industry techniques for integration of supply chains.

Recommendation: The TIME program should regularly review its goals and objectives, as well as its technology path for achieving those objectives, so that it can avail itself of the latest appropriate, well-proven COTS technologies.

Recommendation: It is strongly recommended that the Army Materiel Command establish a standing peer review committee to provide oversight and guidance to the TIME program. The committee should report to Army managers at a level with both budget development authority for the TIME program and overall responsibility for management of munitions. The committee should conduct an annual review of the TIME program, assess progress, and provide guidance on future directions. The committee should consist of a mixture of experts from industry, academia, consultants, and the controls industry.

Finding: The government munitions industry is certainly in need of rehabilitation and upgrading to ensure its readiness to meet the nation's warfighting requirements. Substantial improvements can be made merely by implementing COTS technologies, exercising the equipment to make sure that it works, and then storing the equipment in a manner that prevents degradation. The magnitude of these basic needs, combined with limitations in the defense budget, should preclude government-sponsored development and implementation of leading-edge technologies in the conventional munitions industry unless there are compelling national security needs that cannot be met by COTS technologies. Some of the leading-edge technologies identified by TIME may require large investments over several years and appear to offer only marginal potential improvements when compared with up-to-date COTS technologies.

The committee believes that dramatic strides will continue to be made during the next few years in the commercial development of machine controls, communications and networking capabilities, modeling and simulation technologies, CAD/CAM/CAE systems, enterprise and supply chain integration systems, and the means for enhanced interoperability of these capabilities. Given the lack of a clearly identified, urgent threat to U.S. national security that requires government investment in these capabilities, it appears to the committee that TIME should (1) cease all development efforts, (2) monitor commercial process and modify architectures accordingly, and (3) begin only limited implementation in the conventional munitions industry based on well-defined priorities.

In addition, the committee believes that research efforts should continue in the design and development of smart munitions and advanced energetics, especially through the demonstration and validation phase and perhaps into low-rate initial production. As these advanced weapons become increasingly feasible, the need for improved capabilities to produce conventional munitions will continue to decline. Thus, the highest return to the taxpayer in implementing TIME-identified technologies may be in applying today's COTS technologies to enabling rapid realization and scale-up, if needed, of these advanced munitions.

Conclusion. The heavy focus of the TIME program on Open Modular Architecture Controllers (OMACs) has consumed resources needed for other important dimensions of TIME. TIME should divest its work on OMACs and consider their use only when they are available as well-proven commercial products that exceed the performance of other commercial controllers.

PROGRAM PLAN AND SCHEDULE

Based on the information provided to the committee, there was no financial justification done on either the overall TIME program or the individual subprojects. This is significantly below commercial industry standards, where such analysis is the main tool used to prioritize development projects. Without this kind of criteria, work with poor return-on-investment and low value to the organization's mission may increase project costs.

In terms of detailed scheduling, the TIME program appears to plan only major milestones. While this is a good feedback mechanism to measure progress, it is unsatisfactory planning by industry standards. In an industrial environment, it is considered essential to manage the project to the original delivery dates to enable the promised return-on-investment. Delays nearly always result in budget increases, and a delayed completion means delayed financial benefits. In a project of this size, it is not unusual for several things to go wrong. Industry-standard project management typically has several contingencies built into the project plan to make it possible to encounter problems and still recover. The committee has seen no such contingency planning.

For instance, it can almost be guaranteed that the first introduction of new technology into manufacturing will reveal unanticipated problems that will interrupt production. In commercial industry, as in munitions manufacturing, production commitments must be met. For this reason, commercial industry always has a back-up plan. The committee was not told of a back-up plan to assure that munitions production commitments will survive the expected problems of new technology introduction. Because some of the factories involved are operating at well below their capacity and can easily produce extra product, the committee anticipates that careful planning can readily minimize such disruptions to regular munitions production. However, the TIME program should study and avail itself of the lessons being learned (often the hard way) in commercial industry, regarding, for instance, the massive difficulties that have been encountered by numerous corporations as they attempt to implement complex enterprise resource planning and supply chain integration systems.

Recommendation: The TIME implementation plan should include detailed contingencies for unforeseen disruptions in routine munitions production caused by the introduction of new technologies.

Conclusion: To completely implement all aspects of the TIME program and keep the integrated enterprise fully up-to-date would involve huge expenditures, well beyond what is justified in today's threat environment. However, substantial, prudent, prioritized investments can result in substantial increases in U.S. defense capabilities and cost savings to U.S. taxpayers.

The interconnections between computer systems at the various suppliers and manufacturing facilities will make up a significant part of the TIME program's cost.

Recommendation. The TIME program should perform appropriate cost-benefit analyses for each system interconnection for purposes of creating a cost-effective system and to establish priorities for required interconnections.

The committee believes that as a result of the funding of the program directly by Congress, rather than as part of the internal DoD and Army budget processes, Congress and the Army have provided little specific guidance and oversight for the TIME program. As such, the flow of funds and program accountability are outside the normal chain of command. While this funding indicates the interest of Congress in munitions modernization, it appears that the method of funding has resulted in many of the activities of the program being only loosely coupled with the most pressing needs of the munitions industry. Neither DoD nor the Army feels a sense of ownership.

The basic objectives of TIME cannot be achieved following the current path and within the currently allotted budget. TIME is an effort that is substantially larger and more challenging than those typically undertaken in industry. Yet its budget for early phases of such a program is far less than those typically allotted by commercial industry.

Recommendation: The TIME program should be reconstituted and built into a DoD/Army initiative to be pursued over the next decade. It should be adequately and consistently funded through the formal DoD and Army chain of command, not built on funding that cannot be counted on to continue and that compromises the attempts of program managers to do what is needed for the program. DoD and the Army must assume ownership of TIME if the program is to be successful.

It was beyond the scope of the committee's charge to consider fundamentally different strategies for meeting future production requirements for conventional munitions. However, such strategies may offer the most efficient means for future munitions production. It could be argued, for example, that an industrial base should be designed primarily for production of precision-guided munitions, while also supporting production of conventional munitions.

Recommendation: A high-level Army/DoD study should be undertaken to determine the most effective strategy for meeting future requirements of conventional munitions production. Reasonable alternatives should be identified and evaluated.

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A Totally Integrated Munitions Enterprise ManTech Project

This description of the TIME program was excerpted and edited from the Scope and Background sections of a ManTech document entitled “Totally Integrated Munitions Enterprise ManTech Project,” version f (ManTech 1999). Further details may be obtained from the U.S. Army Armament Research Development and Engineering Center, Picatinny Arsenal, New Jersey.

SCOPE

The purpose of this task is to expand the work and experience created under the Cooperative Research and Development Agreement (CRADA) efforts with the Department of Energy (DoE), Lawrence Livermore National Laboratory (LLNL), in the development of an Open Modular Architecture Controller (DoE OMAC) into an integral part of the Totally Integrated Munitions Enterprise (TIME) ManTech project. The project initially concentrates on establishing a manufacturing enterprise architecture, developing and deploying critical technologies, and validating through testbed and second beta site demonstrations. The DoE OMAC developed by LLNL currently operates in a Windows 95 environment for milling machine operations only. In order to be adaptable to a wide variety of other pieces of Department of Defense (DoD) manufacturing equipment, a Windows NT foundation is necessary. The services outlined constitute the next phase in a program to address and reshape the manufacturing future of both the DoD munitions production base and the DoE weapons manufacturing base. The program will be completed in two concurrent phases and a third ongoing phase:

Phase I will primarily complete the OMAC, first for operation with a milling machine running under Windows 95; this will be referred to as the OMAC version 1. This version will be ported to Windows NT with real-time control extensions; which will be referred to as the version 2. Much of the work on the OMAC version 2 will actually be able to start before completion of the version 1. This is possible because as modules are completed in the OMAC version 1 they can be ported to the version 2.

Phase II will demonstrate the DoE OMAC with integrated compliant modules for discrete logic system for version 1 and standard operator interface made operational on version 2. Concurrent with and based on this OMAC work, Phase II will complete the overall TIME architecture methodology and document for enterprisewide utilization and integration of the OMAC version 2 in an integrated intranet communications manufacturing environment, addressing product realization strategy from design to production for mechanical parts. Phase II will demonstrate this technology and integration of the tools into a collaborative environment and will provide a network with configuration management tools, systems configuration, and management. Testbed facilities for network infrastructure, maintenance, and operation; metal parts machines for machining, installing, and testing of the critical technologies toolset; TIME beta sites; validating demonstrations; support for OMAC integrations; and collaborative work cells will be established and maintained. Demonstrations of TIME will include a validation at government defense and commercial manufacturing facilities, spin-off demonstration of munitions part production to other sites, a plan for demonstrating the TIME concept for munitions electronics, and initiation of the design fora miniaturized global positioning system.

Phase III will extend the work done on the DoE OMAC by adding additional modules and training. The product realization work will be extended to electronics, and training will be developed. A project with TACOM-ARDEC contractors will demonstrate the value of TIME.

BACKGROUND

For at least the last 20 years, manufacturing managers have wanted to take advantage of the promise of computer technology to reduce costs and time-to-market and to produce higher-quality products. The production hardware can be put into place to provide a flexible manufacturing system that can make a variety of products without purchasing new machines. Current technology does not provide economical methods to rapidly and accurately generate and deliver these data to the production machines. The DoD design, testing, and engineering facilities must be able to transfer the manufacturing parameters and procedures in real time from one agile production node to another. In addition, there is no system in existence today that will allow nongovernment-owned facilities to rapidly convert to DoD production in times of national emergency. Because truly open architecture software is not commercially available and because of the learning curve associated with understanding the idiosyncrasies of the applications and developing this magnitude of programming, it is more beneficial and economical for the government to use the knowledge and experience gained by LLNL from their recently completed $20 million CRADA.

The TIME OMAC will enable seamless integration of on-machine product and process data with other enterprise systems and users, while ensuring the ability to deploy technology to the plant floor both cost-effectively and incrementally. From the existing OMAC, an improved OMAC with real-time extensions will be developed and deployed starting with extending the existing

Windows 95 version and then porting to the Windows NT environment with enhanced features and real-time extensions. The controller will support closed-loop processing in an agile environment. This advanced controller will include sophisticated functionality not generally available today, including in-process monitoring and the abilities to sense and correct for process wear, to calculate a process variable based on multisensor data and calibration tables, and to detect tool breakage and take appropriate action under varying conditions. The first implementation will realize a three-axis milling machine capability.

This work will leverage the work accomplished under the DoE Technologies Enabling Agile Manufacturing (TEAM) program and ongoing work being performed under the auspices of the Open Modular Architecture Controller Users Group (OMACUG), thus ensuring general applicability to the needs of both government and commercial organizations. (Note: the DoE OMAC will be modular, but to avoid confusion with OMACUG standards compliance and also express this modularity, the term DoE OMAC will be used henceforth to refer to the DoE controller.) With ongoing TEAM and OMACUG participation, LLNL is to continue as the developer of the DoE OMAC to ensure both that it is functional with the enterprise and that no proprietary hardware or software not capable of conforming to the OMACUG's application programming interface standards creeps into the system. LLNL is the vital key to successful system integration and is responsible for all design activity, networking, and applications to additional machines. LLNL system integration will ensure transfer of the TIME and DoE OMAC technical knowledge developed by LLNL in Phase I to be successfully incorporated into all efforts throughout Phase II.

B Machine Controllers

INTRODUCTION

This appendix starts with a brief history of computer numerical control (CNC) and its relationship to its synergistic technologies—programmable logic control (PLC), computer-aided design (CAD) and computer-aided manufacturing (CAM). The next section gives a brief overview of the basic required functions of a machine controller. Whether or not the hardware and software architecture is "open," these functions are basic to all machine tool controllers. The rationale for open architecture control follows, based primarily on information taken from the Open Modular Architecture Controller (OMAC) User's Group web site (available at <www.arcweb.com/omac>), and an article titled "Open, Modular Architecture Controls at GM Powertrain," written by the General Motors Power Train Group (GMPTG) (Taylor et. al. 1996). The next section describes the history of the OMAC research projects funded by various federal agencies, including the objectives and results from each project. This is followed by a section that describes current applications of systems that use commercially available open controllers.

HISTORY OF COMPUTER NUMERICAL CONTROL AND PROGRAMMABLE LOGIC CONTROL

Shortly after World War II, John Parsons at the Massachusetts Institute of Technology (MIT) envisioned the use of mathematical data to actuate a machine tool. In June 1949, the U.S. Air Force funded a program to develop a mathematical or numerical control system for machine tools. By 1951 an electronic control system had been assembled, and application studies were begun. By 1953 enough data had been assembled to indicate the practical possibilities that could be developed. Bendix Corporation purchased the patent rights that originated in the MIT research project and produced the first commercial production computer-controlled or numerical control (NC) unit for machine tools, which was introduced in 1955. New impetus was given to NC development when the Air Force placed orders for 100 new NC contour-milling machines. Four companies built the machines: Cincinnati Milling, Giddings & Lewis, Kearney & Trecker, and Morey Machinery. Five companies built the controls: Bendix Aviation, Cincinnati Milling, General Electric, Giddings & Lewis, and Electronic Control Systems, Inc.

Since then, NC or CNC, as it was later called, has evolved from simple relay logic-based systems to systems driven by paper tape to the sophisticated real-time control systems available today. Thus these machine controls have a long history, for a technology in the computer era. Because the machine tool industry is conservative and machines are built for long lives, there is an enormous legacy of equipment, used every day, that is controlled by all vintages of these controllers. It is not uncommon to see controllers designed in the 1970s in use in shops today. The challenge of upgrading legacy equipment exists for all of the U.S. fabrication industry, not just the munitions industrial base. It should be noted, however, that a substantial portion of the production equipment in the munitions industry was built before the advent of numerical controls.

Along with the development of the controls, software was developed to automate the creation of the code needed by CNCs to move the tool correctly and make the part. Programs for complex parts can have thousand of lines of intricate, detailed code and take hours to execute. Most of the parts fabricated by the munitions industry are relatively simple and straightforward by comparison. Since the scope and complexity of the part-programming problem can be significant, CAM applications were created to assist the CNC programmer with the preparation of part programs. Today, CAM programs are critical, integral applications in support of CNC and the successful use of computer control on machine tools on the shop floor.

In parallel with the development of CNC and CAM, the mechanical design world began to make the conversion from manual design on drafting boards to design using computer hardware and software tools. As these CAD systems evolved and grew in capability, they were an obvious candidate to link with CAM and CNC for an automated solution to the challenge of converting design into finished components. The data path of CAD/CAM/CNC is a major component of traditional computer-integrated manufacturing (CIM) and is in common use today using a wide variety of CAD, CAM, and all vintages of controllers. Standards have been developed to enable the transfer of data between these systems. As the technologies have changed and matured, significant issues have been raised regarding current standards. There are groups working on the changes needed to keep up with the new ways of representing and transferring data.

Competitive pressures, including the increased velocity of product development and the trend toward outsourcing of fabrication, are driving large and small companies to reduce product realization time. As a result, an enormous software industry has grown up to meet this need. Several commercially available packages address the need to create the data and transfer it to control the machines needed to fabricate the components.

PLC, an additional class of equipment controller, is closely related to CNC. Richard Morley of Modicon is credited with invention of the PLC in 1968 and its unique Ladder List programming language. PLC differs from CNC in that the focus of CNC is on motion control in multiple degrees of freedom through servo drives. CNC usually uses a relatively small number of so-called discrete input/output control points that, for instance, can monitor the status of a switch or energize a relay to open a valve. PLC designs are usually optimized to handle discrete event types of applications with limited capabilities for controlling servo-driven axes. The categories of PLC and CNC controllers are slightly blurred, since a CNC always includes PLC functionality and some PLC controllers can accommodate limited motion control. An understanding of the differences between the two types of controls is important because the publicity regarding OMAC and some of the “open” control references are focused exclusively on PLC types of applications, although it can be difficult to discern from the titles.

COMPUTER NUMERICAL CONTROL FUNCTIONS

CNC systems are unique computer-based systems that are used as tools by human operators to perform a number of complex fabricating functions in real-time, safety-critical environments, often around the clock. When a CNC malfunctions, the expensive part being fabricated usually must be scrapped. If the safety part of the system fails, the operator can be in significant danger from the high-power, high-speed operations of the machine. Therefore, CNC systems must be robust and reliable to meet the safety and performance goals of the manufacturers that use them. The primary functions of a CNC controller include the user interface, programmable logic control, and the machine executive.

User Interface

The user interface enables operators and technicians to

- Enter, edit, and execute standardized (RS-274) machine motion and process instruction programs, called part programs;
- Input part programs from outside sources, such as disks, RS-232 serial links, network links or even paper or Mylar tape (in older systems);
- Manually move the machine axis to operate functions such as coolant and spindle controls during setup or diagnostics;
- “Dry run” the motions of a program on a graphical display to ensure that the program works correctly before risking an expensive in-process component; and
- Perform diagnostics and debug operational problems.

Safeguards and interlocks are controlled by the CNC controller to prevent human access to moving components during operations.

Programmable Logic Control

PLC software, with extensions for CNC motion control, is developed by the machine tool builder (MTB), using tools provided by the control manufacturer or an outside source. The PLC software is used to customize the controller for a particular machine configuration. This software executes in near real time (<10 milliseconds per cycle), reading input sensors or "flags" from the part program or machine executive (see below), executing logic (e.g., if this sensor is on, then close that relay, which shuts a valve) as determined by the MTB, and setting outputs as instructed.

Machine Executive

Software developed by the control manufacturer that exerts control over all of the other software processes is known as the "machine executive." The executive is responsible for executing the motions and functions commanded by the part program. As each line (called a "block" by the CNC community) is executed, the executive parses the commands in the block and hands off the information to the appropriate software or hardware module.

Motion commands are given to the trajectory control so that the appropriate electrical signals can be sent to the motion servos on each of the axes. For example, block "N0100X1.0 F1.0" is interpreted by the controller to mean that the 0100 line commands the controller to move the X axis to the X= 1.000 position at a 1in./min feed rate. The trajectory controller compares the current position of the axis (say X=0.500) to the desired position (X=1.000) and sends an electrical signal to the servo to accelerate the tool along the axis to the commanded velocity and to start moving to the new position. As the servo accelerates the tool, the controller monitors the speed and position in order to achieve the commanded speed, then decelerates the tool and stops it along the axis at the required position.

Other commands control switches to turn on or off functions like coolant pumps or to open or close chucking devices. For example, block "N0200 X1.0 Y2.0 F5.0 M15" means that the 0200 line commands the controller to move the tool along the X axis to X=1.000, while simultaneously moving the tool along the Y axis to Y=2.000 at a 5 in./min feed rate and turning on the coolant pump. The M15 command is sent to the programmable applications logic executive (see above) so that the appropriate relay is energized to turn on the coolant pump.

The executive monitors and controls the status of a number of other parameters in the machine. For example, whether or not a commanded block has been completed before something else happens is often important and can be monitored.

The Rationale for Open Architecture Controls

Since CNC controllers are expected to perform a number of critical operations in real time, and because allowing users to modify the software opens the control manufacturers to reliability and liability issues, the control manufacturers have historically been extremely reluctant to allow users to modify the executive functions of the control. Users are almost never allowed access to this level of the controller. Likewise, the machine tool builders (MTBs) are usually the only ones allowed access to the programmable logic functions of the machine. Thus, end users of the controller generally have access only to the part program portion of the control software. Thus, the end users must rely on the MTB or controller manufacturer for special modifications to the programmable logic and executive functions of the machine. Since most requests for special modifications are required by very few customers, there is a large impact on the engineering and software resources of the controller manufacturer to execute, document, and support the requested changes, which serve only a limited segment of the client base. Controller manufacturers want to maximize their returns, so they often charge high prices for the modifications and give special modifications a low priority. Thus, special changes often take a long time to make or are never achieved at all.

This has been frustrating for the research and special machine community, because sensors developed to monitor process physics and control algorithms developed to close the control loop are very difficult to integrate with the proprietary controls. Commercial users, such as the General Motors Powertrain Group, were frustrated by (1) the lack of a common look and feel in the user interface of various suppliers, (2) a need to reduce control system development and integration time, (3) the inability to incrementally upgrade or scale functionality up or down in their controllers when application requirements changed, and (4) an inability to insert in-house proprietary engineering knowledge. This frustration with (1) the reluctance of the control manufacturers to open their controls; (2) other business practices of the manufacturers, such as the high cost of “approved” repair parts and add-ons like upgraded memory (in the microcomputer world memory prices dropped rapidly while the CNC world saw memory prices go up); and (3) the forced bundling of other machine tool components like servo drives with the control led to the call from end-users for open systems.

PREVIOUS PROGRAMS RELATED TO OPEN ARCHITECTURE CONTROLS

Nearly all of the federal government technology development programs on “OMAC-like” controls trace their origin to a gathering hosted by the Air Force Manufacturing Technology (ManTech) Directorate called the DoD Machine Tool Manufacturing Technology Development Conference, held in Dayton, Ohio, in June 1987. The conference identified research needs for machine tools and processes of the future for the Department of Defense (DoD). Industry and academic participants identified the need (among others) for advanced CNC capabilities and more accessibility to the inner workings of the NC controls of the day.

Advanced manufacturing projects that had been frustrated in their attempts to integrate several sensors and unique control algorithms into the era’s CNCs made the need for more open controls apparent. The Air Force was sensitive to this problem, since two recent projects funded by Air Force ManTech were challenged by the capabilities of the CNCs of the day. These projects were the Integrated Welding and Grinding (IWAG) project executed by Battelle Columbus Labs from 1982 to 1987 and the Intelligent Machining Workstation

(IMW) project executed by Cincinnati Milacron and Carnegie Mellon University from 1987 to 1990.

The IWAG project objective was to reduce the costs to repair jet engine turbine blades for the U.S. Air Force by developing the technology to repair the blades using an automated, unmanned process that could run 24 hr/day. Since the blades had previously been in service, the first step was to use a coordinate measuring machine (CMM) to measure the geometry of each blade to determine the repairs required. The geometry data for each blade moved with the blade and was used by six unique process steps on four machine tools. Two of the machine tools had two CNCs in an integrated work cell that simultaneously performed operations on shared parts. Additional information was added to the part data package by the subsequent welding and grinding operations. The data/part synthesis and movement of information using the proprietary closed CNC and PLC controls of the day proved to be one of the most challenging tasks of this information-intensive project.

The IMW program was the earliest attempt to create a “part from art,” using an automated, unmanned machining workstation that could rapidly create a good first part from a feature-based electronic part description. The project results, which included the development of machining sensors, flexible fixtures, robotic loading devices, and expert systems for process planning, were not truly integrated into the “closed” architecture CNC machine tools.

Both projects found it extremely difficult to integrate unique sensors and control algorithms and to exchange information between subsystems. Some of the IMW team went on to address these problems by developing the concept of and building an open architecture controller in the late 1980s. This team is credited with the introduction of the Open Architecture Manufacturing concept in 1988. The Machine Tool Open System Advanced Intelligent Controller (MOSAIC) began working at New York University in that year. The MOSAIC program took advantage of the vastly expanding microcomputer industry. Using generic products and open systems, a large number of third-party products were developed that could be obtained by microcomputer users simply by referring to a microcomputer magazine and ordering with a toll-free number. A second-generation version, the MOSAIC-PM, was built later at the University of California at Berkeley using commercially available components. It is currently used to manufacture components as part of the integrated manufacturing and design environment, where parts are designed at the Department of Energy’s Sandia National Laboratories in Livermore, California, and fabricated at Berkeley.

Another important early research effort that addressed the open architecture control issue was called the Next Generation Workstation/Machine Controller (NGC) specification for an Open System Architecture Standard program. This program ran from 1987 to the publication of the final specification in August 1994. The deliverable for this project was a document that described a structure for the development of open architecture systems for manufacturing. The project was a paper exercise and the structure developed was not used for a hardware or software deployment during the course of the 7-year program. In fact, in the summary section of the NGC document, the authors noted that, “Taken together, the application architecture and the profiling structure form a firm foundation for NGC system development; they do not, however, represent a complete methodology that would support immediate development of a national, commercial NGC product base" (NCMS 1994).

There are two elements that are missing from the overall system that would facilitate the adoption of the NGC approach: (1) fully populated and widely accessible implementation component libraries, and (2) a family of tools for system design, integration, and validation. The difficulty lies in developing the initial libraries and toolset, although, once developed, it seems clear that they could become important commercial products. This program met with limited success but triggered several new programs that continued where the NGC project left off.

The National Institute of Standards and Technology (NIST) Enhanced Machine Controller (EMC) program, which ran from the early 1990s to at least 1995, grew out of NIST's involvement with the NGC program and the real-time control system architecture. The EMC program developed a modular definition of components for machine control and a specification for their interfaces, with broad application to robots, machine tools, and CMMs. These components include individual axis control, coordinated trajectory generation, discrete input/output, language interpretation, and task planning and execution. The intent of the specification was to support interoperability of components provided by independent vendors. NIST has installed a machine tool controller based on these interfaces on a 4-axis horizontal machining center at GMPTG. The intent of this demonstration system is to validate that the interfaces are comprehensive enough to serve a demanding application and to demonstrate several key concepts of open architecture controllers: component interoperability, controller scalability, and function extension. In particular, the GM-NIST EMC demonstrates interoperability of motion control hardware, scalability across computing platforms, and extensibility via user-defined graphical user interfaces. In addition, the EMC specifications have been implemented on a variety of machines, both at NIST and elsewhere.

Yet another open architecture program was a $52.6M, DOE cooperative research and development agreement (CRADA) with teams of researchers from LLNL, Los Alamos National Laboratory (LANL), and a Louisiana-based company called ICON (Industrial Controls Corporation, Inc.). CRADA was established to spur development of software microcomputer-based control of machine tools. The 3-year program started in late 1994 and was credited with demonstrating the concept on a three-axis milling machine at Los Alamos in March 1995, just 6 months after the project was initiated. LLNL developed the underlying real-time operating software for agile manufacturing, LANL wrote human-interface software, and ICON wrote application-specific modules to be inserted into the controller and worked with GM and the Pratt-Whitney Division of United Technologies, Inc. In the OMAC arena, the TEAM program (1994 to 1997) was the immediate predecessor to the TIME program. The TEAM project had a thrust area, titled intelligent closed-loop processing that included several tasks that focused on open architecture controller issues. The first was a NIST task to write the application programming interfaces for the initial open architecture controllers. It was anticipated that the application programming interfaces would evolve as open architecture control (OAC) requirements mature. The next task was to develop an OAC for a Ford Motor Company drill press located at Ford's Scientific Research Center. Another task was to add volumetric error compensation, in an OAC environment, to a Bostomatic mill at LLNL. The next task was to add volumetric error compensation, in an OAC environment, to a T-base lathe at LLNL.

COMMERCIAL APPLICATIONS FOR OPEN ARCHITECTURE CONTROLLERS

GMPTG made the first claim in the literature to installation of a microcomputer-based open architecture CNC controller in an industrial setting with a VME-based system installed on a Kearney and Trecker four-axis milling machine in 1991. This is the system built by NIST for GMPTG under the EMC program and was not a commercially available system, even though the components were off-the-shelf because of the need for custom integration of the components.

In 1998 GMPTG began implementing (for two new engine programs) a plan to have a customizable, microcomputer front-end using Microsoft Windows as the operating system for each proprietary controller and to use a standard Serial Real-Time Communication System (SERCOS) interface between the controller and drives.

Commercial open architecture controllers began to appear in the marketplace with the advent of the Hurco Ultimax controller in the mid-1990s. Since this beginning, other competitors have appeared, including Aerotech, Delta Tau, and MDSI (Manufacturing Data Systems, Inc.). Recently, the main line CNC controller makers have begun to offer open controllers as a part of their product lines.

C Open Modular Architecture Controller

INTRODUCTION

The following section reviews two key operations within the TIME program. The Melt Pour and Twin Screw Programs provide unique challenges to the TIME Infrastructure. Each program's operation and control scenarios are examined in detail to determine their overall control requirements. These operations demonstrate the demanding control requirements of the TIME project.

MELT POUR OPERATION

Overview

The Melt Pour Operation, as the name suggests, involves the melting and pouring of High Energy Material (TNT) into projectiles. We will examine the basic operation of the Melt Pour Operation looking for control points and requirements. The goal of the following examination will be to identify the control scenarios needed to create an automated Melt Pour Operation. As seen in the diagram below the Melt Pour Operation Consists of the following components:

- Projectile Component Pre-Heaters—Brings Projectile Components to Proper Temperature
- Melt Kettle—Prepares TNT Material
- Pour Machine—Dispenses TNT Material
- Cooling Bay—Controls Cool Down of Filled Projectile
- Probe Machine—Inspects TNT Material for Desired Temperature Profile

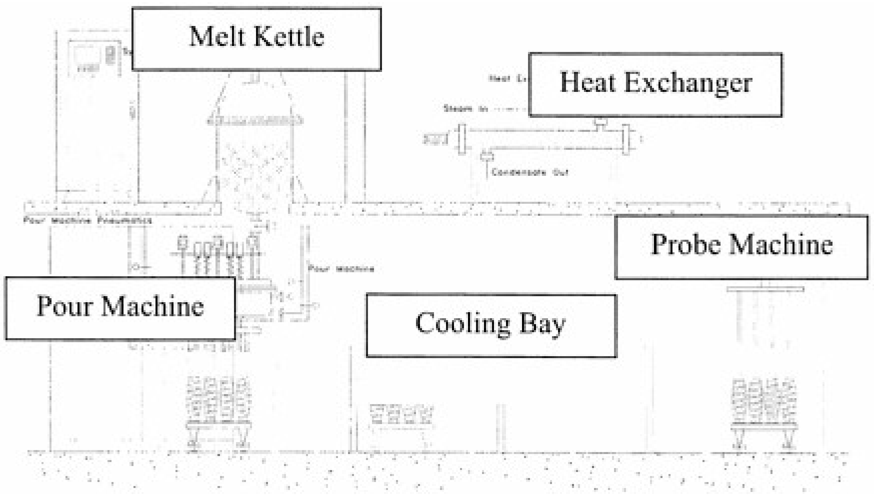

Figure C-1 Melt-pour operation

The following examination includes additional components that are not seen in the existing diagrams but are necessary to achieve an automated Melt Pour Operation. These additional components are:

- Integrating Controller—OMAC System Controller
- Integrated Projectile Handling System—Moves Projectiles between Identified Components.

Each of these Components and their operation scenarios is examined below.

OPERATIONAL SCENARIOS

Projectile Component Pre-Heat

The first part of the operation involves heating the projectiles and funnels to the determined temperature. The Funnel and Projectile Preheat Ovens bring the funnels and projectiles to a desired temperature. The OMAC Controller would be responsible for controlling each of these ovens against a model of temperature profiles. The controller must be capable of responding to external commands determining the actual profile of the projectile temperature. The projectile and funnel pre-heat ovens are seen below.

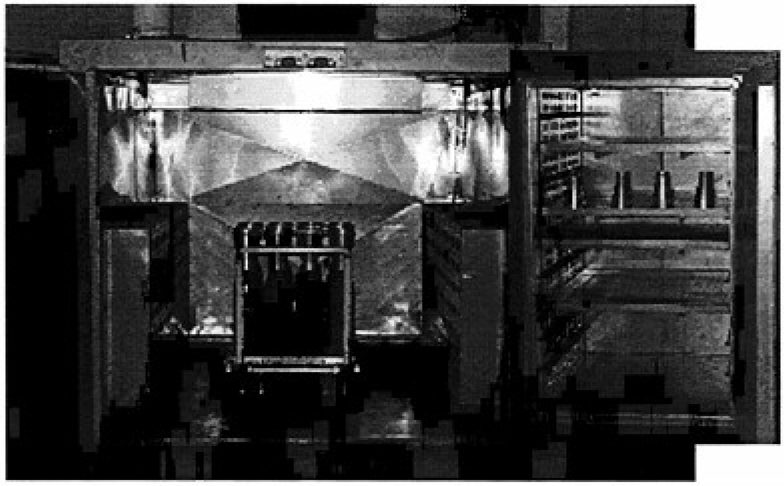

Figure C-2 Funnel and projectile preheat oven

The complexity of this control problem is seen in the automated scenario of an integrated projectile handling and delivery system. The OMAC Controller must determine the proper exit temperature from the Pre-Heaters for each projectile component given the following factors:

- Temperature Loss Model of each Projectile Component
- Temperature and Humidity in Facility
- Time Delay Based on Process times for Projectiles ahead of current components.

While the Pre-Heaters do not need to perform these calculations it is the responsibility of the Pre-Heaters to respond to the temperature profiles based on these calculations.

Melt Kettle

The melting portion of the operation involves combining two forms of TNT. A solid TNT known as Feather Rice is added to molten TNT known as heal. This process of introducing the solid to molten TNT is known as seeding. The exact composition and control of all the materials within this process greatly influences the overall effectiveness of the projectile. A metal grid is used to melt the TNT to form the molten heal. The OMAC controller will have to close loop control the temperature of the grid.

The Kettle is agitated to maintain the mixture. Several operational problems result when delivery of the feather is not precise. For example, the agitator can bind if more that 40% feather is added. This creates a critical situation where the high-energy material is stuck in process. This operation problem illustrates the need for precise feed and agitation control.

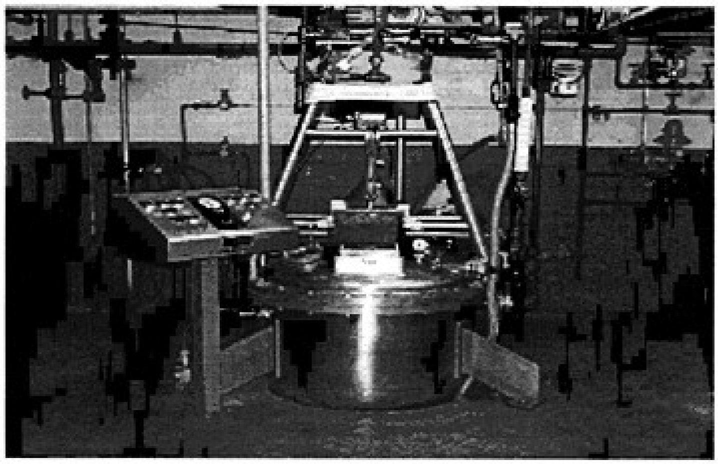

Figure C-3 Melt kettle

The Feather is introduced into the heal through controlled vibratory feeders. The feeders employ constant amplitude vibration with duty cycle to precisely deliver material.

The OMAC controller will control the agitators and vibratory feeders to maintain the precise mixture as required. The TIME program is investigating sensor technologies that can provide information on the exact mixture in the Kettle. This information can then be utilized to close the loop on the seeding and agitation operations. The overall mixture within the kettle will effect the vibration and agitation times for the Kettle control station.

Pour Machine

The Pour Machine consists of a TNT delivery mechanism to 15 projectiles. The current system utilizes pneumatically controlled valves that servo against the total kettle weight to determine material flow. A flow sensor will be included in the automated process allowing for precise real-time control over the pneumatic valve and directly over the material flow rate. The OMAC controller will use the sensor information to precisely contorl material flow to each projectile. The current pour mechanism can be seen in the figure below.

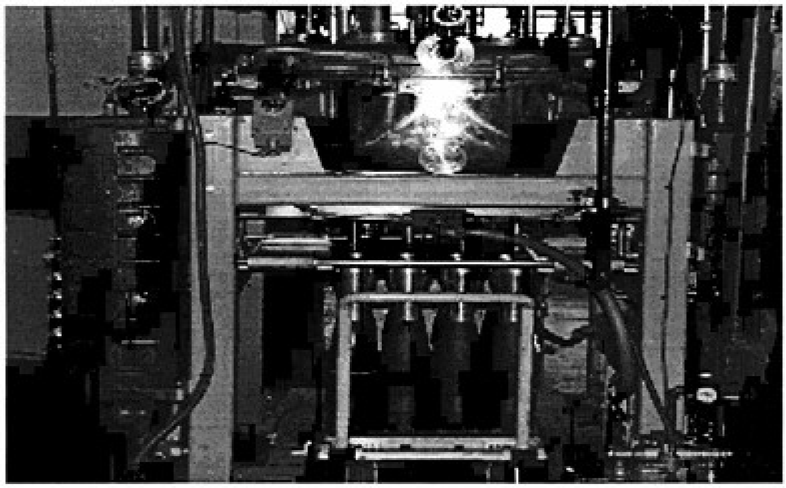

Figure C-4 Pour mechanism

Cooling Bay

The cooling bay allows for the controlled cooling of the filled projectiles. A heat exchanger is utilized to ensure the exact cooling rates desired by the process model are achieved. The current cooling bay configuration is seen below.

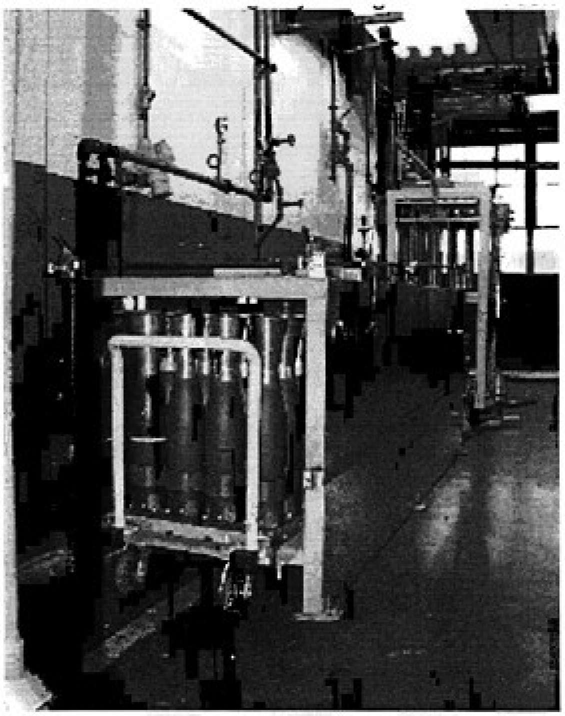

Figure C-5 Cooling bay

The OMAC controller will monitor the projectile temperatures and modulate the heat exchanged to precisely control the overall cooling process. The model for the cooling will account for the following factors:

- Exit temperatures from Pour Machine
- Material transit time from Pour Machine to Cooling Bay
- Facility temperature and humidity
- Desired cooling profile for projectile type
- In process material ahead of the projectile buggy
- Heat exchanger characteristics and performance

All of these requirements are combined to produce the cooling profile and the inputs to the cooling bay control. As with other models within the melt-pour operation the computation will not be within the facility. The models require tremendous processing power and it will be necessary to run these computations offsite. Several parameters within the model are dynamic and will require constant closed loop monitoring.

Probe Machine

The final station of the Melt-Pour operation is a probing station that determines the projectile temperatures at designated points within the projectile. These temperatures are used to determine the anticipated effectiveness of the projectile. The goal of the automated system will be to utilize these measurements to help improve the upstream process. The temperatures can be used to control several upstream parameters:

- Pre-Heat Oven Temperature
- Melt Kettle Temperature
- Cooling Bay Profile

The OMAC controller’s ability to provide an integrated system allows for the closing of control loops throughout the Melt-Pour System.

Integrated Projectile Handling System

The automation scenarios of the Melt-Pour operations are contingent on having an integrated projectile handling system. Various material handling systems are available throughout the industry. The Melt-Pour operation relies heavily on precise temperature controls in both heating and cooling of all materials involved. The delivery times associated with moving from one component to another require a deterministic mechanism to move the High Energy Material and projectiles from one station to another. Fine temperature control is lost if the transit time between stations is not deterministic. An automated material handling system will provide feedback to the process models that are determining heat-up and cool-down profiles. The projectile handling must be capable of integrating between various facilities. The material must be tracked within a single system. The current delivery times from the Projectile Handling System will be used as feedback to the process models to maintain the overall system performance.

TWIN SCREW OPERATION

Overview

The twin screw operation involves mixing of various forms of energetic material along with solvent to form various propellants. Extrusion by definition is the process of compacting and melting material and forcing it through an orifice in a continuous fashion. We will examine the basic operation of the twin screw looking for control points and requirements for both the controller and model. The autonomous twin screw operation requires a very tight integration between the control system and a full model of the extrusion process. The goal of the following examination will be to identify the control scenarios needed to create an autonomous twin screw operation. As seen in the diagram below the twin screw operation consists of the following components:

- Material Feed Area—solid powder and solvent
- Extruder Barrel—actual mixing area
- Die Area—exit area for mixed material
- Takeaway area—conveyor belt and indexing table area

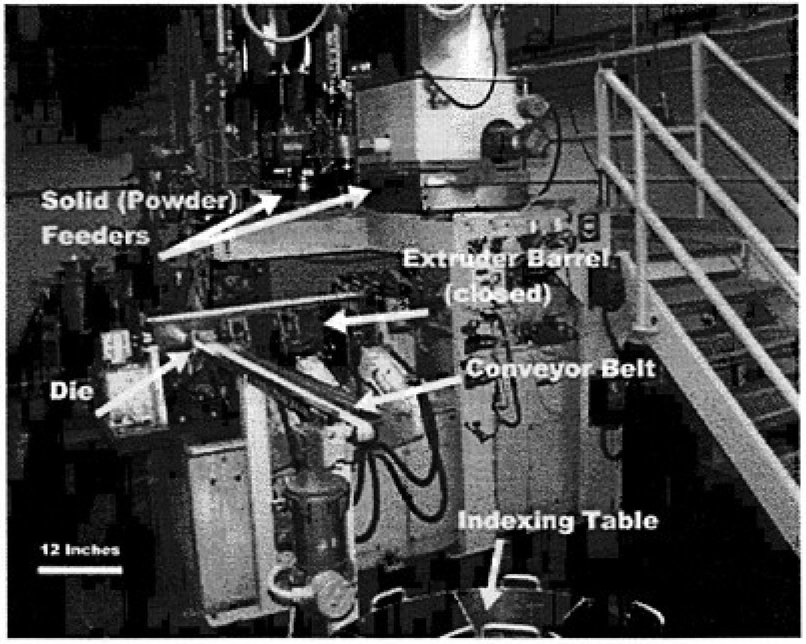

Figure C-6 Twin screw operation

The following examination requires an integrated control system to achieve an automated twin screw operation. Each of these components and their operation scenarios are examined below.

Operational Scenarios

Material Feed

The first part of the operation involves introducing the energetic material and solvent into the extruder. The energetic material is in a powdered form. The powder and solvent are introduced in mix zone 1 and zone 2 as seen below. The facility consists of three solid loss-in-weight feeders, one liquid loss-in-weight feeder for lacquer and one liquid loss-in-weight feeder for the solvent.

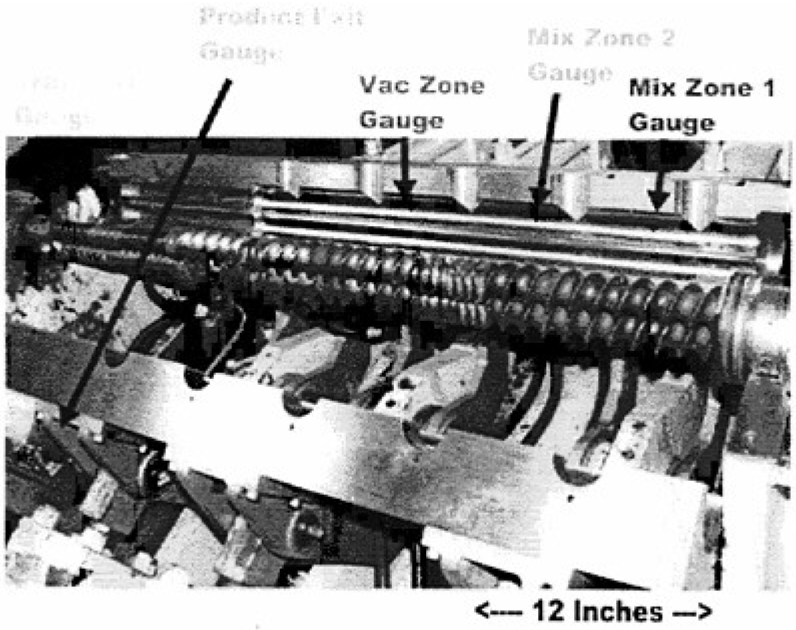

Figure C-7 Twin-screw extruder for energetics processing

The solid material is introduced by utilizing a single screw feed. A loss-in-weight controller is verifies the proper amount of material flow. External agitators ensure proper product feed. The OMAC controller is required to perform the motion control over the screw axis as well as the agitators. The agitators are controller by constant amplitude vibrations under various duty cycles. This technique resembles a PWM controller. High-speed control over the duty cycle is required.

The solvent is feed with a zenith gear control system into two injection ports. The solvent is introduced to zone 2. The entire process model will dictate high-speed flow rate changes both the solid and solvent materials. The OMAC controller will have to provide controller response to these new set points.

Extruder

Once the material is in the extruder, temperature and pressures are maintained to guarantee product consistency. The Vacuum section of the extruder is responsible for allowing the removal of appropriate amounts of solvent to ensure the desired product characteristics. Temperatures are controlled with four zone heating control. Five surface temperature, water temperature and pressure taps are used to provide control feedback.

Die and Takeaway Area

At the discharge port of the extruder is a die that is designed to form a cylindrical product. There are separate hot and cold temperature controls for the die area. The takeaway belt from the die area must work to slightly pull the material from the die. Conveyor speeds too high will result in product tearing. Vision systems will be investigated to identify torn product sections that cannot be used. The actual conveyor speeds will by set by the process model accounting for the exit pressure from the die and the material characteristics of the propellant.

CONTROL REQUIREMENTS

The following tables summarize the control requirements for the Melt-Pour and Twin Screw Operations as well as the entire TIME Program. They provide a requirements list in evaluating the ability of a particular controller to meet the TIME programs needs.

Melt-Pour Program

Table C-1. Melt Pour Program Control Requirements (McWilliams 2000a)

Component	Control Domain	Description
Pre-Heat Ovens	Dual Oven Control Capability Closed Loop Temperature Control Oven Temperature Model	Controls Two Commercial Ovens Actual Set Points are determined by process Model Model Parameters • Temperature Loss Model for Each Component • Material Delivery Time • In-process Delays based on material upstream
Melt Kettle	Closed Loop Temperature Control Closed Loop Single Axis Motion Control Closed Loop Vibrator Control Melt Process Model	Controls Metal Grid to a profile as dictated by process model. Agitator Control—Speed set by process model. High Speed time based control over vibrator on/off times to achieve flow rate as dictated by the process model. Model Parameters • Desired Projectile Characteristics • Vibrator Performance • Feather Flow Rate Sensor • Grid Temperature Sensor
Pour Machine	Closed Loop Pneumatic Valve Control Pour Process Model	Servo against flow sensor. Model Parameters • Desired Projectile Characteristics • Valve Performance • Material Flow Rate Sensor
Cooling Bay	Closed Loop Temperature Control Cooling Bay Process Model	Servo against internal temperature sensors. Model Parameters • Exit Temperature from Pour • Material Transfer Time • Facility Temperature and

		Humidity • Desire Profile for Projectile • In-Process Material ahead of Buggy • Heat Exchanger Performance
Probe Machine	Interface to Probe Data	Interface to Probe Data for Model and Statistics.
Projectile Handling System	Integrated Material Handling Control Physically Distributed Full Material Tracking	Material Handling Must work from System Controller and respond to supervisory control. Components are not collocated. Delivery times must be tracked and reported in real-time.
Communications Infrastructure	High Speed Communications System Wide Data Access Physically Distributed	Models must be able to be calculated and return results in milliseconds. All components of the control system will produce and consume information from the models. Models will be run offsite to meet program goals. Pre-Heat Ovens and Melt-Pour are in different buildings with Integrated Material Handling.

Twin Screw Program

Table C-2. Twin-Screw Program Control Requirements (McWilliams 2000b)

Component	Control Domain	Description
Material Feed	Motion Control Closed Loop Pneumatic Valve Control Closed loop Agitator Control	Single axis control over solid feeders. Servo against flow sensor. Actual Set Points are determined by process Model
Extruder	Closed Loop Temperature Control	Model set points must be maintained in the 4 heating zones in the extruder barrel.

	Motion Control	Single Axis control over the extruder speed. Process model dictates the desired extruder speeds.
Die and Takeaway Area	Closed Loop Temperature Control Single axis motion control	Closed loop temperature control over the hot and cold zones of the die area. The process model dictates that temperature set points.
Process Model	Complex Model is inprocess component to the OMAC Controller.	Model Parameters: • Extruder, Barrel and Die Configurations • Material Feed and Speed • Propellant Usage • Temperature and Pressure Sensors • In-Process Material ahead of Buggy • Heat Exchanger Performance
Communications Infrastructure	High Speed Communications System Wide Data Access Physically Distributed	Models must be able to be calculated and return results in 100s of milli-seconds. All components of the control system will produce and consume information from the models. Models will be run offsite to meet program goals. Pre-Heat Ovens and Melt-Pour are in different buildings with Integrated Material Handling.

TIME Project Controller Requirements Summary

The TIME Projects as discussed in the previous two sections provide a requirements list to potential control products.

The heavy reliance on models to close the loops throughout the architecture require each point within the control architecture to be able to produce performance data and respond to new control commands based on the model results. The timings throughout the system require the interactions with the model happen over deterministic, high-speed communications channels.

The TIME programs infrastructure requires that the models often be run at locations other than the production facility.

The overall control system for either the Melt-Pour or the Twin Screw Programs will require a flexibility and complexity rarely found in controller implementations. The complexity, consequence of risk and tight integration required between all levels of the controller architecture, reach that of a fighter aircraft. These types of controls systems are characterized by:

- Closely controlled proprietary architectures
- Large portions developed in assembly language specific to proprietary hardware
- Black Box systems where “Open” is not required (and perhaps not desirable)
- Modifications require large Development Programs
- Ongoing Support Programs are required for the life of the product (to maintain expertise, provide enhancements, correct operational ‘issues’ and ‘bugs’, provide spare parts and hardware upgrades, etc.)

However, these characteristics do not satisfy the requirements of the TIME program. The TIME program requires a true “Open” controls architecture that allows for creation of control loops not originally predicted by the controls developer because of lack of technology or models.

As summarized in the preceding tables, the following major features characterize the TIME controller:

- Model Based Control
- Closed Loops throughout the Controls Architecture
- High Speed Deterministic Communications between Facilities
- Hard Real-Time Capability (Guaranteed Maximum Response Time)
- Single Paradigm for Models, PLC and Motion Expression
- Success Dependent on Extensibility and Portability

This requirements combination creates two additional major requirements:

- Need for a Single Development Environment
- Portability of Logic

Need for a Single Development Environment

The ability of the TIME Program controllers to be extended will be directly dependent on their approachability. The expression of the control logic and the ability to easily document the control architecture will determine the extensibility of the TIME controllers. These two TIME programs tightly mix PLC, Complex Motion and Process Models. This tight integration must be reflected in the development of the control system.

A controls engineer must be able to work within a single environment which focuses\their train of thought on the development of the control system and not how to integrate different subsystems and languages. The developer must not be constrained by having to move from one environment to another because they needed to touch an I/O bit during a motion loop. Having to move from one package for models and then another for sensor interfacing is not acceptable. This shifting of paradigms from one environment to another causes constraints on the controls system that will stifle the controls engineer’s ability to close loops and create a tighter integration. The controls engineer needs to concentrate on the production tasks and have an environment that supports free flow expression of this logic.

The ability to extend the control system will determine its eventual life span. An open, extensible control system, contained in a single development environment must be a stated goal for the TIME program. This requirement will serve as a major discriminator for controls candidates.

Portability of Logic

A key goal for the TIME program is to be able to leverage commercial installations to increase the overall production capability in times of need. This seemingly simple goal proves to place heavy requirements on control system candidates. The complexity and integration of the TIME program requires a control system architecture that supports all of the “Openness” of the Army’s facilities.

The only way to ensure that the commercial site is able to deliver the needed product will be to have the controls logic moved to the commercial location. This true “Portability” requires an electronic standard to be used for the expression of the controls logic. The TIME project cannot afford to recreate the entire control system for each production site. There exists no validation capability to ensure that the logic expressed in one controls paradigm matches that of another. The development of the control system would be constrained by a “Least Common Denominator” of the logic expression at all commercial sites.

STATE OF COMMERCIAL CONTROLLERS

In light of the TIME program controller requirements, a review of the current state of commercial controllers is required. The cost effectiveness of COTS integration technologies has lead to major innovations within the controls community. Industries characterized by their slow response and long product cycle times are now being forced to reach desktop type one-year product cycles. This demand for product features and marketing pressures has led to the heavy use of undefined terms within the controls community. The use of the word “Openness” has nearly led it to have no meaning. The challenges of the TIME program provide a substantial set of requirements that help focus in on the definition of “Open.”

- Model based control
- Closed loops throughout the controls architecture
- High speed deterministic communications between facilities
- Single Paradigm for models, PLC and motion expression
- Hard real-time support
- Success dependent on extensibility and portability

Commercially available products from companies like Siemens, Modicon and Rockwell are characterized by several basic similarities:

- Division of PLC logic and complex motion
- Difficult integration between vendors
- DCOM as an integration standard

Each of these characteristics is detailed below.

Division of PLC and Complex Motion

The division of PLC and Complex Motion has led to motion capabilities being characterized by strict parameter adjustment to preprogrammed control laws. There exist several products, like the Rockwell Control Logic, which do allow for the introduction of Motion Function Blocks into the PLC logic. The Motion capabilities of these blocks have the following capability:

- Electronic gearing
- Master-slave following
- Pre-programmed profile following

With each of these modes there are several parameters for the adjustment of maximum accelerations and velocities. The control laws governing these capabilities are fixed and are not accessible. It is not possible to directly control the gains or modify the feedback loops.

For complex motion capability the vendors provide separate packages. These packages offer more complex parameter and gain adjustment. The packages provide several preprogrammed control laws like torque mode and velocity control. The motion products do not allow for actual control law substitution.

These separate PLC and complex motion packages require the controls engineer to use different development environments depending on the control problem.

Lack of Integration Between Vendors

IEC-61131 has provided standard requirements for the expression of control logic. There are five basic expressions of logic, which include Ladder, Structured Text, Function Block, Instruction List, Sequential Function Charts and others. These standards present the appearance of interoperability of various vendors' products.

The PLC Open committee is enhancing and certifying vendors against different levels of the IEC1131 standard. The definition of being IEC-61131 compliant under PLC Open's definition requires that a particular product meet 80% of the requirements to achieve certification. This allows for tremendous variation within vendors products.

The greatest change of portability between the various companies is in Structured Text expression of logic. Structured Text is a formal language defined by IEC that expresses the logic of a controls solution. The 80% requirement of PLC Open has allowed for various parts of the Structured Text language to be supported by a particular vendor and not on others. To implement truly portable logic, the least common denominator between all candidate control product's implementations of structure text must be used. This severely constrains the controls solutions.

Structured text does not include the required support for complex math based motion algorithms. The structured text can call into preprogrammed function blocks as seen in the simple motion algorithms as described previously.

The IEC-61131 effort has tried to create a standard enabling portability between PLC vendors, but because of the allowance of partial compliance true portability has not been met. There are no like efforts for the Motion Control Industry.

DCOM Sets Integration standard

DCOM has emerged as the Defacto standard for communications integration between controller components. DCOM must be examined against the constraints of the TIME program controllers. DCOM was designed for the desktop world. Real-time to the desktop world is seen in terms of seconds. DCOM is built on top of COM, binary interface standard for Component Encapsulation.

DCOM has been heavily leveraged by the HMI world to provide easy integration to commercial controllers. The OPC effort within the controls community has shown the power of the DCOM technology when applied to realistic control problems.

The actual implementation of DCOM still provides several challenges to the controls engineer:

- Difficult Domain-to-Domain Integration
- Possible large packet delivery latencies
- Large timeouts on packet failure

Each of these areas is examined below.

Difficult Domain-to-Domain Integration

DCOM requires that a user meet all security requirements on the server machine before they can access a particular server. This means the user must have an identical account with identical privileges on the client and server machines. This model works well within a particular network domain but is difficult to configure across domains. The normal solution is to configure the user as an administrator across both machines, which violates all security policies in place to protect the system. This configuration is difficult within a single company's product let alone between two different vendors. Domain-to-Domain DCOM integration difficulties have prevented true enterprise wide integration of control information.

Possible Large Packet Delivery Latencies

DCOM communications transmit on the normal IT infrastructure Ethernet. The loading of the corporate network is highly unpredictable. DCOM ‘s use in real-time situations requires deterministic bounded response, which is impossible to guarantee with unknown additional traffic. There are technologies, such as high-speed switches, that help to alleviate this problem but they do not solve the problem throughout an enterprise which may span the globe.

Large Timeouts on Packet Failure

DCOM was built on top of OLE technologies from Microsoft. One of the basic legacy issues with DCOM is the several minute timeout of a packet failure. A client or server is not notified of a delivery failure for up to 6 minutes. This characteristic has been identified as a major impediment for DCOM adoption into critical roles.

The DCOM standard has led to major revolutions within the HMI and SCADA industries. However, DCOM's reach into the real-time world is limited by its configuration, latencies and large timeouts.

COMMERCIAL CONTROLLER SHORTFALLS

The market has latched onto the “Open” buzz word and uses it throughout their literature. The lack of a true definition for open has lead to major confusion. A quick market study without an in-depth technical analysis of the motion solutions can lead to a false sense that the market is full of “Open” control products. The TIME project offers a very challenging view of the word “Open” characterized by:

- Support for Model based control
- Ability to close loops throughout the controls architecture
- High speed deterministic communications between facilities

- Single paradigm for models, PLC and motion expression
- Success dependent on extensibility and portability
- Hard real-time support

The commercial controllers fall short in trying to meet each one of the TIME challenges:

Table C-3 TIME Requirements and Shortfalls

TIME Requirement	Commercial controllers shortfall
Support for Model Based Control	Model Based Controls are constrained by the limitations of the development language. Structured Text has only rudimentary math capabilities limiting the complexity of the model and requiring the model to run on the controller.
Closed Loops throughout the Controller PLC & Motion	TIME's definition of closing loops is not constrained to a single control discipline. No commercial controllers allow for closing loops to levels that include changing control laws and interacting with the entire control architecture.
High Speed Inter-Facility Deterministic Communications	DCOM is heavily utilized as communications infrastructure and does not meet real-time deterministic requirements because of latency and timeout constraints.
Single Development Paradigm for Models, PLC and Motion Logic	Market is led by Simple Motion and Modeling extensions to PLC products. No Product provides the combination of complex modeling and motion along with PLC activities. Most vendors require separate products for each area.
Extensibility and Portability	Attempts at a portability standard from PLC Open will always fall short because of acceptance of partial compliance. Extensibility is limited with the single control product (PLC, Motion) and does not allow for product growth between these areas.
Hard Real-Time Support	Most major PC based Control products do not currently support Hard Real-Time across PLC, Motion and Modeling.

The "Open" solution from the OMAC team allows for a unique solution to meet all of the TIME requirements. It allows controls providers to modify the basic behavior of the controller to fit their methodology.

Table C-4 TIME Requirements and OMAC Features

TIME Requirement	OMAC Feature
Support for Model Based Control	Introduction of Model Algorithms are allowed throughout the controller independent of whether it involves axis position, I/O or calculated variables.
Closed Loops throughout the Controller PLC & Motion	OMAC allows for access to all variables within the control system independent of type. Data is not classified as being motion, PLC or model data. Control Algorithms have open access to all data within the control system.
High Speed Inter-Facility Deterministic Communications	The TIME project has lead the way in developing high speed T1 communications specializing in Remote site connectivity.
Single Development Paradigm for Models, PLC and Motion Logic	The OMAC development environment provides a single location for the expression of all logic independent of whether it is PLC, Motion or Model. The class definitions for all layers of the control system are immediately available to the controls developer without switching tools.
Extensibility and Portability	The JAVA expression of the OMAC controller provides an industry standard mechanism for the control logic of all aspects of the control to move from location to location. The single development environment allows for the extensibility of all aspects of the control system without respect to it being a PLC, motion or modeling problem. The development concentrates on the control problem and does not have an arbitrary partitioning.
Hard Real-Time Support	The OMAC controller is built on top of VenturCom's RTX environment. The RTX environment is recognized by Microsoft and the Controls Industry as the leading Hard Real-Time extension to Microsoft's Windows NT environment.

The OMAC controller provides a unique solution to the controls requirements of the TIME project. The OMAC controller has been designed with the entire lifecycle needs of the controls engineer in mind, without the legacy constraints that hinder a majority of the control industry's products. The engineers and designers of control systems are provided with a single development environment that supports a "train of thought" development effort. The engineer does not have to worry about whether the algorithm necessary for the control activity needs data from a PLC or motion system. The engineer concentrates on the problem and the OMAC environment makes sure they have access to all data necessary to solve the problem. In short, the OMAC environment allows the controls engineer to concentrate on the controls problems and not the problems of the development environment.

D Biographical Sketches of Committee Members

Joe H.Mize (chair) is Regents Professor Emeritus at Oklahoma State University, where he has served in several positions since 1972, including Director of the Center for Integrated Manufacturing and Head of the School of Industrial Engineering and Management. Prior to that, he served as Professor of Industrial Engineering at Arizona State University and Director of the Center for Automated Engineering and Robotics. Dr. Mize brings to the committee his broad experience with enterprise integration. His research interests include the development of a framework for integrating manufacturing enterprises; the development of a comprehensive modeling and simulation environment; enterprise modeling, design, and optimization; and analysis and design of integrated management control systems. He is the author or co-author of 7 engineering texts and co-editor of a 200-volume industrial engineering textbook series. Dr. Mize is a fellow of the Institute of Industrial Engineers, as well as a past national president. He received the Frank and Lillian Gilbreth Industrial Engineering Award in 1990. Dr. Mize is a member of the National Academy of Engineering and has served on numerous NRC committees. He has also served as a member of the Manufacturing Studies Board and is now a member of the Board on Manufacturing and Engineering Design.

John G.Bollinger is John Bascom Professor of Industrial Engineering and Dean Emeritus at the University of Wisconsin at Madison, where he has been a faculty member since 1960. He served as Dean of the College of Engineering for 18 years, Chair of the Department of Mechanical Engineering, and Director of the Data Acquisition and Simulation Laboratory. In addition, Dr. Bollinger has been a Fulbright Fellow to Germany and England. His research interests include computer control of machines and processes, robotics, design of production machinery, analysis of dynamic systems, and technology innovation and entrepreneurship. His industrial experience includes serving as founding Chair of the Wisconsin Center for Manufacturing Productivity and as a past member of the Board of Directors of numerous companies, including The Rexnord Corporation, Cross and Trecker Corporation, Nicolet Instrument Corporation, and Unico, Inc. He currently serves as a Director of the Andrew Corporation, Kohler Company, Berbee Information Networks, and Cummins Allison Corporation. Dr. Bollinger has published over 100 journal articles, 2 textbooks, and holds 11 U.S.

patents. He is a member of the National Academy of Engineering and a member of the Board on Manufacturing and Engineering Design. In addition, he chaired the Committee on Visionary Manufacturing Challenges and has served on numerous other NRC committees.

Reggie J.Caudill is Professor of Industrial and Manufacturing Engineering at the New Jersey Institute of Technology (NJIT), as well as Executive Director of the Multi-Lifecycle Engineering Research Center. He brings to the committee his extensive expertise in automation and robotics. Dr. Caudill has taught at NJIT since 1990 and was the founding director of the NJIT Center for Manufacturing Systems. Previously, he taught at the University of Alabama for 5 years, serving as Director of the Robotics and Computer Graphics Laboratory and Technical Coordinator for the Bevill Advanced Manufacturing Center. Prior to that, Dr. Caudill served as Co-Director of the Industrial Automation and Robotics Program at Princeton University, where he taught for 7 years. His primary area of research is the integration of advanced machine and computer technologies with applications in multilife-cycle processes, systems, and automation. Current research includes the development of a flexible automated system for assembly of optoelectronic devices; investigation of the performance of machine tools with contactless elements; and ultraprecision, environmentally conscious manufacturing systems. He is the author of over 75 technical publications and a member of the editorial advisory board of *Product Design and Development*. He was the 1981 recipient of the Ralph E.Teetor Award from the Society of Automotive Engineers.

Ray E.Eberts is Associate Professor of Industrial Engineering at Purdue University, where he has taught since 1983, as well as Director of the Purdue Laboratory for Usability Studies and Director of Continuing Engineering Education. In 1990, he was an Invited Professor at Nippon Telephone and Telegraph's User Interface Laboratories in Yokosuka, Japan. In 1991, he was Visiting Associate Professor in the Industrial and Systems Engineering Department of the University of Southern California. Dr. Eberts brings to the committee his expertise in the area of human-technology interfaces. His research interests include the development of theories based on cognitive science and human performance for the effective design of information displays, the identification of relationships between individuals' cognitive goals and user interface designs, and the use of neural networks for online intelligent assistance and filtering information for complex environments. Applications of his research have included second-order control systems, computer-aided design, process control, computer programming, and on-line education. Dr. Eberts received the Presidential Young Investigator Award from the National Science Foundation in 1987. He is the author of over 90 refereed journal articles, conference proceedings, book chapters, and books, including *User Interface Design,* a textbook relating cognitive science to user interface design.

Mark S.Fox is Professor of Industrial Engineering at the University of Toronto, with concurrent appointments in the Department of Computer Science and the Faculty of Management Science. In addition, he is Head of the Enterprise Integration Laboratory and Director of the Graduate Program in Integrated Manufacturing. Previously, Dr. Fox was Associate Professor of Computer Science and Robotics at Carnegie Mellon University and Director of the Center for Integrated Manufacturing Systems. Dr. Fox brings to the committee his extensive experience in enterprise integration. Previous research has focused on the application of artificial intelligence to factory planning and scheduling problems; constraint reasoning as applied to job shop scheduling; and the application of artificial intelligence to simulation. His current research focuses on enterprise engineering, constrained-directed reasoning, a unified theory of scheduling, and enterprise modeling and coordination theory. Dr. Fox is cofounder and past president of Carnegie Group, Inc., a knowledge-based software company that focuses on engineering, manufacturing, telecommunications, and banking applications. While a consultant for Westinghouse Electric Corporation, he designed one of the first real-time sensor-based diagnosis systems dealing with errorful sensors. This system was recognized as one of the top 100 engineering achievements of 1986. He is a Fellow of the American Institute for Artificial Intelligence and a joint Fellow of the Canadian Institute of Advanced Research and PRECARN.

Rajit Gadh is Professor of Mechanical Engineering at the University of Wisconsin-Madison, as well as Director of the Complex Artifactual Design through Integration of Information Technologies Consortium and Director of the Integrated Computer-Aided Research on Virtual Engineering Design Laboratory. He brings to the committee his extensive expertise in virtual and concurrent design. His research interests include Internet media for visual collaboration, geometric algorithms for rapid product realization in Internet-based virtual environments; the creation of a multimedia environment for shape and design; geometric algorithms that allow for shape features to be determined from nonlinear solid models in support of virtual prototyping of complex-shaped part designs; and the integration of knowledge of manufacturability, die design, and part design into the web-based collaborative computer-aided design system. He is the author of numerous journal articles. Dr. Gadh is active in a number of professional organizations, including the American Society of Mechanical Engineers (ASME), the Society of Manufacturing Engineers, the Society of Automotive Engineers (SAE), the Institute of Electrical and Electronics Engineers, and the American Society of Engineering Education. He was the 1993 recipient of the Ralph E.Teetor Award from the SAE, the 1995 recipient of the National Science Foundation CAREER Award, and the 1993 recipient of the Eastman Kodak/ASME Best Paper Award for his research on features-based design.

David Greenstein is currently Managing Director at Commerce One where he is responsible for enterprise level IT architectural solutions. He is also responsible for Supply Chain Management and Enterprise Security. Prior to Commerce One, David Greenstein was Project Manager in the Information Systems and Services Division of General Motors Corporation, where he worked for 17 years. Mr. Greenstein brings to the committee his expertise in enterprise integration in an industrial setting. His responsibilities included the development of a corporate strategic information system architecture for manufacturing at General Motors. In addition, he was a member of General Motors' Corporate Enterprise Architecture Council, the goal of which is to develop a state-of-the-art corporatewide strategic information system architecture. Earlier responsibilities at General Motors included leading the research and development for an information system designed to improve agility and implementing corporate information and control systems. Prior to that, Mr. Greenstein worked as a research and system developer for the Academy of Sciences in the former USSR.

Thom J.Hodgson is Professor of Industrial Engineering at North Carolina State University (NCSU) and Director of the Integrated Manufacturing Systems Engineering Institute. He has also served as Head of the Department of Industrial Engineering at NCSU, Director of the Division of Design and Manufacturing Systems of the National Science Foundation, Professor of Industrial and Systems Engineering at the University of Florida, Operations Research Analyst for the Ford Motor Company, and as an Officer in the U.S. Army Transportation Corps. His research interests include scheduling, production and inventory control, manufacturing systems, and applied and military operations research. He is a Fellow of the Institute of Industrial Engineers and a member of the Institute for Operations Research and the Management Sciences, and of the Society of Manufacturing Engineers. He is the author or co-author of four book chapters and 60 journal articles and has served as editor-in-chief of *IIE Transactions,* international associate editor of the *Belgian Journal of Operations Research, Statistical and Computational Science,* and a member of the international editorial board of the *Journal of Design and Manufacturing*. He served for 6 years as a member of the Army Science Board.

Richard L.Kegg retired as Vice President of Technology and Manufacturing development at Milacron, Inc., where he worked for 44 years in R&D, Engineering, and Marketing, including managing the flexible manufacturing systems business. Dr. Kegg remains active in a number of professional societies including the International Institution for Production Engineering Research and the Society of Manufacturing Engineers. He has served on advisory boards for several organizations, including U.S. Air Force ManTech, the Oak Ridge Centers for Manufacturing Technology, Lawrence Livermore Labs, the National Center for Manufacturing Science, and the NIST Manufacturing Labs. He has published several papers and was the recipient of the Gold Medal from the Society of Manufacturing Engineers. He has served on the NRC Unit Manufacturing Process Research Committee and the NRC Panel for Manufacturing Engineering and is currently a member of the NRC Board on Manufacturing and Engineering Design.

Richard E.Neal is Executive Director of the Integrated Manufacturing Technology Initiative (IMTI), a not-for-profit organization focused on delivering solutions to the most important challenges that manufacturers face. In his more than 30 years in manufacturing R&D, he has held many positions from development engineer to R&D manager. For the past 10 years, he has focused on visionary programs that support the nation's manufacturing infrastructure. He has served as Program Manager for the Technologies Enabling Agile Manufacturing (TEAM) program, as one of three principal investigators for the Next Generation Manufacturing (NGM) project, and as the project manager for the NGM follow-on called Integrated Manufacturing Technology Roadmapping (IMTR). IMTR delivered a set of manufacturing technology plans that have been received as the most comprehensive and broadly representative roadmaps (plans) ever produced. IMTI is the continuation of this series of national programs and is charged with the mission of facilitating the implementation of the technology roadmaps.

Deborah S.Nightingale is Professor of Practice in the Department of Aeronautics and Astronautics and the Engineering Systems Division, Massachusetts Institute of Technology, where she has taught lean enterprise integration since 1997. She brings to the committee her extensive expertise in the use of computer technology in the integration of manufacturing enterprises. Prior to that, she was head of Strategic Planning and Business Development at AlliedSignal, where, among other things, she significantly improved enterprisewide productivity, profitability, and market share; established globalization strategies and identified new business development and growth opportunities; and developed a master plan for manufacturing operations. During her 17 plus years at AlliedSignal, she held management positions in operations, strategic planning, business operations, and engineering. In addition, she chaired the Garrett Engine Division Computer Integrated Manufacturing Committee. Prior to joining AlliedSignal, she worked at Wright-Patterson Air Force Base, where she served as program manager for computer simulation modeling research, design, and development in support of advanced man-machine design concepts. She is the author of 40 publications and the recipient of a number of awards, including the Patricia Kayes Glass Award from the Air Force Systems Command and the Outstanding Manager of the Year Award from the American Society for Training and Development. She is a past President and Fellow of the Institute of Industrial Engineers and a member of the National Academy of Engineering, where she has served as Chair of the Industrial and Manufacturing Section Peer Committee. In addition, she served on the NRC Committee for Defense Manufacturing in 2010 and Beyond.

Jeffrey L.Ruckman is the founder of Resultant Manufacturing Services (RMS), a technology-based firm with extensive expertise in program management, business assessment, and the optimization of manufacturing and business processes. Mr. Ruckman's expertise includes planning and implementing of computer integrated manufacturing systems; the design and development of high-precision, automated manufacturing equipment for both commercial and military end-users; and assessment of the economic impact of manufacturing and information automation. He has obtained certification from the Society of Manufacturing Engineers as an Enterprise Integrator. Prior to forming RMS, Mr. Ruckman was a Senior Consulting Associate with Coopers & Lybrand and managed a variety of successful modernization projects at small and medium manufacturers in upstate New York. In previous positions at Battelle Columbus Laboratories and at Gelzer Systems, Inc., he led state-of-the-art equipment and information systems development projects involving vision-system-assisted robotic electronics assembly and computer-numerical-control-based aerospace component repair systems. He is a member of the following organizations: Society of Manufacturing Engineers, American Society for Quality Control, Optical Society of America, and American Precision Optics Manufacturers Association. He has also authored several technical reports.

Paul K.Wright is the A.Martin Berlin Professor of Mechanical Engineering at the University of California at Berkeley, as well as Co-Chair of the Management of Technology Program, and Associate Dean for Distance Learning and Instructional Technology. He provides the committee with extensive expertise in robotics. Prior to joining the University of California faculty in 1991, he spent 5 years at New York University as Professor of Computer Science and Director of the Robotics and Manufacturing Research Laboratory. Before that, he spent 8 years as Professor of Mechanical Engineering at the Robotics Institute of Carnegie Mellon University. His research interests include machining and robotic applications in flexible manufacturing systems, the development of expert systems for manufacturing, and rapid prototyping. Dr. Wright received the Outstanding Young Manufacturing Engineer Award from the Society of Manufacturing Engineers in 1980, the Ralph J.Teetor Award from the Society of Automotive Engineers in 1981, and the Blackall Award from the American Society of Mechanical Engineers in 1985. He is the author of numerous articles, book chapters, and books and holds a U.S. patent with an additional patent pending. Dr. Wright has served on the NRC Committee to Study Information Technology and Manufacturing and the NRC Committee on Rapid Prototyping Facilities in the U.S. Manufacturing Community, and he is a former member of the Manufacturing Studies Board (now the Board on Manufacturing and Engineering Design).

E Glossary

Application program interface (API).	The interface (calling conventions) by which an application program accesses operating system and other services. An API provides a level of abstraction between applications and ensures portability of applications from different sources.
Architecture.	A model of arrangement and connectivity for the physical or conceptual components of a system.
Computer-aided design (CAD).	A combination of computer software and hardware used in conjunction with computer graphics to enable engineers and designers to create, manipulate, and change designs without conventional paper drafting.
Computer-aided engineering (CAE).	A wide range of computer tools used to analyze and optimize proposed product designs via mathematical and simulation models. CAE tools are also used to optimize the processes for manufacturing a product.
Computer-aided manufacturing (CAM).	The use of computers to control and monitor manufacturing elements, such as robots, computer numerical control machines, storage and retrieval systems, and automated guided vehicles. At the lowest level, CAM includes programmable machines controlled by a centralized computer. At the highest level, large-scale systems integration includes control and supervisory systems.
Computer-integrated manufacturing (CIM).	The integration of computer systems in a manufacturing facility. Integration may extend beyond the factory into the facilities of suppliers and customers. CIM integrates systems that handle everything from ordering to shipment of the final product, including accounting, finance, management, engineering, and manufacturing. The scope of CAM is generally limited to the factory floor, but CIM generally extends beyond the factory floor.

Concurrent engineering (CE).	An approach in which product design, process development, and manufacturing preparations are carried out simultaneously.
Data markup language (DML).	A specification for a fixed data exchange format for Internet applications.
Design Cockpit.	An interface to a Web Information Manager (WIM) that enables users to perform some subset of process activities, such as an iterative study of design trade-offs, in an automated manner.
Distributed enterprise.	An organization that has operations in more than one geographic location.
e-business.	Using the capabilities of Internet technology, including turning raw information and data into actionable intelligence, to conduct business electronically.
e-commerce.	Buying, selling, and exchanging information electronically.
Enterprise architecture.	The body of knowledge for designing, building, operating, and modeling enterprises. The architecture contains guidelines and rules for the representation of the enterprise framework, systems, organization, resources, products, and processes.
Enterprise framework.	A set of standards governing behavior, organization, processes, resources, communication, and information that gives reference, meaning, orientation, or viewpoint to an enterprise and the systems and subsystems related to it.
Enterprise integration (EI).	The process of combining the diverse corporate and social cultures brought on by global partnerships, including the safeguarding of intellectual assets, remuneration based on the value added by each participating organization, local work practices, social customs, liability sharing, and team-based cooperation for the overall benefit of the enterprise.
Enterprise modeling.	The generation of representations (models) of an enterprise or part of an enterprise (e.g., process models, data models, resource models).
Enterprise resource planning (ERP).	An accounting-oriented information system for identifying and planning enterprisewide resources needed to take, make, ship, and account for customer orders. An ERP system differs from the typical MRP II system in technical requirements such as graphical user interface, relational database, use of fourth-generation language and computer-assisted software engineering tools in development, client-server architecture, and open-system portability. More generally, a method for the planning and control of resources needed to make, take, ship, and account for customer orders in a manufacturing, distribution, or service company.

Expert systems, or knowledge-based systems.	Interactive computer programs that help users with problems that would otherwise require the assistance of human experts. Expert systems capture knowledge in rules that can be communicated to others as advice or solutions. The programs often stimulate the reasoning process used by human experts in certain well-defined fields.
Extended enterprise.	A group of companies that work together as a consortium and act as a single business entity to satisfy a particular set of customer needs. The extended enterprise consists of customers, the original equipment manufacturer, and multiple tiers of suppliers down to the raw material level.
Extensible markup language (XML).	A simple dialect of SGML defined by the World Wide Web Consortium.
Firewall.	A combination of hardware and software designed to make a Web site secure.
Flexible manufacturing.	The ability to manufacture a wide variety of hardware types (products) in a cost-effective and timely manner and the ability to adapt to the changing needs of the organization (customer). Flexible solutions emphasize highly skilled personnel, flexible equipment, facility layouts, and manufacturing processes optimized for a rapidly changing business environment.
G and M codes.	In RS-274, G and M codes cause the machine to change from one mode to another, and the mode stays active until some other command changes it implicitly or explicitly.
Hypertext markup language (HTML).	A hypertext document format used on the Worldwide Web. Tags and directive information are embedded in the document to delimit text and indicate special instructions for processing it.
Information technology (IT).	A general term for computing and telecommunications equipment, plus the software and data that operate on that equipment, and the standards and architectures used to manage it all effectively.
Initial Graphics Exchange Specification (IGES).	A standard for translation of graphics data from one application to another.
Integrated enterprise.	A business or organization composed of individuals who have acquired knowledge and skills to work with others to make the organization a greater success than the sum of each individual's output. Integration includes increased communication and seamless coordination between individuals and within and across teams, functions, processes, and organizations over time.

Integrated product and process development (IPPD).	The discipline of developing products and the processes used for their manufacture in parallel, so as to reduce the time and cost of moving products from concept to production. Commonly accepted as the next step beyond the practices of concurrent engineering.
Integrated product realization (IPR).	A concept of totally interconnected and interrelated processes for creating product, from generation of the initial product concept and definition of its requirements, to optimization of the design of the product and its manufacturing processes, and to eventual creation of the product itself.
Integrated supply chain.	An association of customers and suppliers who, using management techniques, work together to optimize their collective performance in the creation, distribution, and support of an end-product.
Integration.	The act of linking heterogeneous processes and equipment across companies and among collaborating companies (suppliers, partners, customers). It is particularly important in the area of communication and information exchange.
Intellectual property.	Property created through creative, intellectual pursuits, manifested as patents, trademarks, copyrights, and designs.
International Organization for Standardization (ISO).	A worldwide federation of national standards bodies from some 130 countries to promote the development of standardization and related activities in the world with a view to facilitating the international exchange of goods and services and to developing cooperation in the spheres of intellectual, scientific, technological, and economic activity.
Internet.	A collection of servers and networks that provide users access to information and applications outside of the company firewall.
Interoperability.	The ability of two or more systems, subsystems, products, or applications to work together and share information or inputs and outputs.
Intranet.	A secured network of Web pages and applications that can be accessed by anyone within a company firewall.
Lean manufacturing.	A set of practices intended to remove all waste from a manufacturing system, especially by eliminating or greatly reducing nonvalue-added activities. “Lean” encompasses concepts such as just-in-time, Kaizen, Kanban, empowered teams, cycle time reduction, small lot manufacturing, and flexible manufacturing.

Life cycle.	The collective set of phases a product or system may go through during its lifetime (e.g., concept definition, development, production, operation and support, demilitarization, and disposal).
Local area network (LAN).	A communication system within a facility; the backbone of a communication system that connects various devices in a factory to a control center. The LAN, through the control center, allows devices such as computers, bar code readers, programmable controllers, and CNC machines to communicate with each other for control and exchange of information.
Manufacturing resource planning (MRP II).	A direct outgrowth and extension of closed-loop MRP I through the integration of business plans, purchase commitment reports, sales objectives, manufacturing capabilities, and cash-flow constraints.
Materials requirements planning (MRP or MRP I).	A scheduling technique for establishing and maintaining valid due dates and priorities for production orders based on bills of material, inventory, order data, and the master production schedule.
Modeling and simulation (M&S).	The application of a rigorous, structural methodology to create and validate a physical, mathematical, or otherwise logical representation of a system, entity, phenomenon, or process for making managerial or technical decisions.
Munitions industrial base (MIB).	The set of producers and suppliers that collectively manufacture munitions for the U.S. Includes GOGO (government-owned, government-operated), GOCO (government-owned, contractor-operated), and COCO (contractor-owned, contractor-operated) facilities.
Neural network.	(1) A computer simulation of the brain, (2) Self-organizing systems of simple interconnected processing units that possess a learning rule and are capable of learning.
Next-generation manufacturing (NGM).	A 1996/97 program to develop a broadly accepted, industry-driven model for a next generation manufacturing enterprise and action plans that individual companies can use to help plan, achieve, and sustain world-class manufacturing. NGM was funded by the National Science Foundation, Department of Defense, Department of Energy, National Institute of Science and Technology, and several industry sponsors and participants.
Open-architecture control (OAC).	A machine control architecture in which servo loops may be accessed and customized by control engineers at the user organization.

Open Modular Architecture Controller (OMAC).	A type of industrial machine controller intended to allow the integration of off-the-shelf hardware and software components into an overall infrastructure using a non-proprietary operating system that is a de-facto standard.
Open systems.	Systems that are designed to interconnect with a variety of products that are commonly available, allowing a large degree of vendor independence.
Outsourcing.	The procurement of goods and services from suppliers outside of the corporation.
Partners.	Companies that agree to work together, often for a specific period of time or to achieve specific objectives, and share the risks and rewards of their relationships.
Partnership.	An agreement between two companies, often formalized in a contract.
Process model.	The defined description or representation of a process.
Product Data Exchange Using STEP (PDES).	A standard for exchange of geometric data (e.g., CAD files, graphics).
Product data management (PDM).	The process of, or a system for, managing all information about a product as it moves through the engineering and manufacturing lifecycle. Generally includes functions such as management of engineering drawings, processing of change notices, and configuration control.
Product model.	Information about a product captured in a standard representation format (e.g., a CAD file).
RS-274.	A programming language for numerically controlled machine tools.
Servo or servomechanism.	An automatic control system where the output is compared with the input through feedback, either continuously or intermittently, so that the difference between the two quantities can be used to control a device or process.
Standard for Exchange of Product Model Data (STEP).	A neutral mechanism for describing product data throughout the life cycle of a product independent from any particular system.
Supply chain.	An association of customers and suppliers who, working together yet in their own best interests, buy, convert, distribute, and sell goods and services among themselves resulting in the creation of a specific end-product.

Supply chain management.	The integration of important business processes, from end-user through original suppliers, that provide products, services, and information that add value for customers and other stakeholders.
Technologies Enabling Agile Manufacturing (TEAM).	A joint industry/government program to develop, integrate, demonstrate, and validate manufacturing technologies that support the vision of manufacturing as a seamless, tightly integrated process from concept to delivery.
Totally Integrated Munitions Enterprise (TIME).	An Army initiative aimed at modernizing the U.S. munitions industrial base through the adoption of CAD/CAM, networking, COTS production equipment, system integration, and supply chain management practices.
Transparency.	The extent that participants are aware of activities throughout the supply chain.
Virtual enterprise.	An opportunity-driven partnership or association of enterprises with shared customer loyalties designed to share infrastructure, research and development, risks, and costs and to link complementary functions.
Web Integration Manager (WIM).	A software element permitting combination of multiple design-and-manufacturing-related functions, including product design, process planning, process simulation, and fabrication controls, into a single interface using World Wide Web standards.

F Acronyms

ADAPT	Advanced Design and Production Technologies (DoE)
API	application program interface
APT	automatically programmed tool (programming language)
ARDEC	Armament Research, Development, and Engineering Center
CAD	computer-aided design
CAE	computer-aided engineering
CAM	computer-aided manufacturing
CMM	coordinate measuring machine
CNC	computer numerical control
COCO	contractor owned/contractor operated
CORBA	Common Object Request Broker Architecture
COTS	commercial-off-the-shelf
CRADA	cooperative research and development agreement
DCOM	Distributed Component Object Model
DFM/A	design for manufacturing and assembly
DoD	Department of Defense
DoE	Department of Energy
DoL	Department of Labor
DOS	disk operating system
ECAD	electrical computer aided design
EDI	electronic data interchange
EI	enterprise integration
EMC	Enhanced Machine Controller (NIST)
EPSS	Electronic Performance Support System
ERP	enterprise resource planning
GMPT	General Motors Powertrain
GMPTUG	General Motors Powertrain User Group
GOCO	Government owned/contractor operated
GOGO	Government owned/government operated
GPS	global positioning system

HFMI	Highly Filled Materials Institute
HMI	human-machine interface
ICON	Industrial Controls Corporation, Inc.
IMW	intelligent machining workstation
IT	information technology
IWAG	integrated welding and grinding
LAN	local area network
LANL	Los Alamos National Laboratory
LCMS	Louisiana Center for Manufacturing Sciences
LLNL	Lawrence Livermore National Laboratory
ManTech	Manufacturing Technology Program
MCAD	mechanical computer-aided design
MIB	munitions industrial base
MIT	Massachusetts Institute of Technology
MOSAIC	Machine-Tool Open System Advanced Intelligent Controller
MRP or MRP I	materials requirements planning
MRP II	manufacturing resource planning
M&S	modeling and simulation
MTB	machine tool builder
NC	numerical control
NDU	National Defense University
NGC	next generation workstation/machine controller
NGM	Next Generation Manufacturing (Program)
NIST	National Institute of Standards and Technology
NRC	National Research Council
NT	Microsoft Windows NT operating system
OAC	open architecture controllers
OEM	original equipment manufacturer
OLE	object linking and embedding
OMAC	Open Modular Architecture Controller
OMACUG	OMAC Users Group
O*NET	Occupational Information Network
PC	personal computer
PDES	Product Data Exchange using STEP
PDM	product data management
PGM	precision-guided munitions
PLC	programmable logic control
PNNL	Pacific Northwest National Laboratory
PRE	product realization environment

RFQ	request for quote
ROI	return-on-investment
SDRC	System Dynamics Research Corporation
STEP	Standard for the Exchange of Product Model Data
STEP-NC	numerical control using STEP
TACOM	(U.S. Army) Tank-automotive and Armaments Command
TEAM	Technologies Enabling Agile Manufacturing
TIME	Totally Integrated Munitions Enterprise
TNT	trinitrotoluene
TSE	twin-screw extruder
WAN	wide-area network
WIM	Web Integration Manager
WWII	World War II
XML	extensible markup language