EVOLUTIONARY CHANGE IN THE DEVELOPMENT OF ENABLING TECHNOLOGIES — A STRATEGIC PERSPECTIVE FOR ADVANCED SYSTEMS DESIGN

by

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Master of Science in Electrical Engineering
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Submitted to the Department of Aeronautics and Astronautics
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ABSTRACT

Post-Cold War shifts in the balance of macroeconomic power have substantially altered the global market forces for the aerospace and electronics industries in the United States. This evolutionary change in world order has induced a period of intense industry competition characterized by strategic growth through mergers and acquisitions among a few major players, particularly for companies which rely on defense prime contracting as chief contributor to return on sales. Emerging from the highly dynamic and often chaotic state of this business environment are strategic initiatives to achieve unprecedented efficiency in the design, development, manufacturing, operation, support, and disposal of advanced systems. This thesis explores the impact of these changes on the U.S. aerospace and electronics industries and presents a model for achieving sustainable competitive advantage as the United States transitions from a manufacturing-based economy to a knowledge-based economy in the global marketplace.

Objectives of this thesis:

- Present a market force analysis for U.S. defense prime contracting in the new world order;
- Establish the concepts of dual-use, technology transfer, and product commercialization;
- Introduce the multi-product adoption model and tool set for system design and management;
- Provide an approach for cost-efficient revolutionary growth in enabling technologies;
- Illustrate thesis concepts using control and sensor system design examples.

Two technology areas have been selected to illustrate the viability of the multi-product adoption model framework and tool set—optimal robust real-time multivariable control and state-of-the-art radar and infrared sensor systems. Both of these technology areas have broad presence in a variety of defense systems, and both have found multiple product applications in a diverse spectrum of commercial markets. By emphasizing cross-market insertion and embracing the concept of process-centered organizations, the model leads very naturally to the concept of core technology development teams (CTDTs) based on the widely recognized integrated product team paradigm. This thesis suggests that CTDTs are an essential element in preserving U.S. leadership in developing advanced technologies, and that CTDTs are most effective by sharing a collective allegiance to a particular technology or family of technologies, but should very rarely be dedicated to a single product.

Thesis Supervisor:
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BIOGRAPHICAL NOTE FROM THE AUTHOR

This thesis presents an application of many concepts from the newly introduced System Design and Management (SDM) Program at MIT. The SDM Program is jointly offered by the Engineering School and Sloan School of Management, with the mission is "to educate future technical leaders in system engineering/architecture and the conception and design of complex products and systems, preparing them for careers as the technically-grounded senior managers of their enterprises."

I am currently employed by Raytheon Company as a Senior Engineer in the System Design Laboratory working on the concept, design, development, simulation, implementation, integration, and testing of missile system technologies. My previous educational background includes a Master of Science in Electrical Engineering and significant work toward the completion of a second Master's degree in mechanical engineering. Research for this thesis coupled with the project work I have been recently involved with at Raytheon have provided a forum to directly apply in practice many of the concepts, principles, and system engineering theory from the SDM curriculum. I have found the SDM experience to be rewarding and valuable, with immediate practical relevance to the changing needs of today's technology development efforts.

ACKNOWLEDGMENTS

I would like to thank Raytheon for sponsoring my participation in the SDM Program. To the many mentors I have had since arriving in 1990, thank you for providing the guidance, support, and motivation to conquer the challenges in achieving many of my personal and professional goals.

To Professor Ed Crawley— my Thesis Advisor, Co-Director of the SDM Program, and Head of the Department of Aeronautics and Astronautics—thank you for providing invaluable insight and for presenting such a unique philosophical perspective into identifying the guiding principles for the successful architecting of complex systems.

To Team SDM (the pilot program students), thank you for being patient, and thank you for an absolutely incredible learning experience—in and out of the classroom. I would also like to thank the SDM faculty and administrative staff for their responsiveness and dedication, especially in making the distance learning aspect of the program run smoothly.

To my friends and family, thanks for everything. Your support, assistance, and encouragement are deeply appreciated and I am greatly indebted.

Robert J. McCarthy
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EXECUTIVE SUMMARY

Demands for enabling technologies in the aerospace and electronics industries have shifted focus to higher emphasis on cost of ownership and on the design of advanced surveillance systems for achieving total electronic awareness. Changes in customer needs will continue to evolve based on the balance of economic power in the global marketplace. An assessment of the impact that reductions in defense spending have made on aerospace and electronics firms indicates that companies must be realigned with a market-driven business strategy model. Research for this thesis suggests that one approach for achieving sustainable competitive advantage is to adopt a policy of developing dual-use technologies under the guidelines of a multi-product adoption model. Specifically, this thesis suggests:

A. Aerospace and electronics industries have evolved considerably due to external factors.
B. Organizations are rapidly responding and adapting appropriately to these market forces.
C. Continued change is required on two fronts—technical redirection and strategic policy.
D. Management of these changes causes stress across intra-organizational boundaries.
E. Improved efficiency is achievable through the multi-product adoption model.
F. Efficiencies from multi-product adoption strategy and tool set are scalable.

Each of these top-level findings is described in detail in this thesis. Items (E.) and (F.) represent a proposed model approach of this thesis and are specifically included in this summary.

E. Improved efficiency is achievable through the multi-product adoption model.
Multi-product technology adoption is an engineering-based approach to leverage modern technical advancements and emerging information systems infrastructure resources to respond competitively to evolutionary changes in the global economy. The model introduces a distinction between core technology development teams (CTDTs) and integrated product teams (IPTs). This distinction is captured in the two different missions each of these teams—IPTs are the customers to CTDTs.

1. *Three Tiers for Achieving Sustainable Competitive Advantage*

i. Strategy
  - Focus on selective dual-use technology development for defense and commercial markets
  - Recognize all opportunities for technology insertion, capture most promising candidates through assessment based on corporate core competencies and existing customer types
  - Maintain a deliberate distinction between the roles and missions of IPTs and CTDTs
  - IPT mission: deliver quality, reliable, cost-efficient products which house core technologies
  - CTDT mission: develop highly modular, easily tailorable technologies for multiple IPTs
  - Leverage the information revolution to facilitate vertical partnering
  - Develop a philosophy of balanced 360-degree product-technology integration

ii. Structure
  - Maintain/establish "permeable boundaries" with flexible interface between CTDTs and IPTs
  - Balance new development efforts with existing product upgrades
  - Align technology/product development with interpreted technical needs/customer "types"
  - Incorporate joint product-technology working groups with IPT and CTDT representatives

iii. Implementation
  - Multi-product adoption tool set for advanced system design and management
  - Modernized information system infrastructure and computer networks
  - Core R&D led by CTDTs with rotating IPT members encourages high level of interaction
  - Vertical integration of key subcontractors using modern information system technologies
  - Participation in selective government-industry-university partnerships

2. Beyond Product Diversification

The multi-product adoption model concept extends far beyond a strategy of basic product diversification or portfolio management. Multi-product adoption is a strategic response to achieve the efficiencies intended by integrated product teams while preserving the unique environment which has cast the United States as a world leader in technological innovation. The model embraces the concept of IPTs, but suggests that core enabling technology development must be protected from total absorption into product-dedicated processes. In the quest for developing cost-effective dual-use technologies and technical innovation suitable for transfer across multiple markets, the processes which have been so successful in the past should not be completely abandoned.

F. Efficiencies from multi-product adoption strategy and tool set are scalable.

One fundamental intention of the multi-product adoption model is that the efficiencies sought can be quantified and measured, and that increases in efficiency are scalable to multiple technologies and diverse industries. This thesis uses the aerospace and electronics industries to identify the utility and potential value of the multi-product adoption model. Once application in the given context is established, it is straightforward to extend many aspects of the model to other technology-based industries. For example, in the development of large-scale network software systems such as those developed by AT&T [85], the concept of IPTs and CTDTs applies directly to the software development process. New non-dedicated telecommunication software modules are developed by technology development groups (the equivalent of CTDTs) and the actual code for customer use is integrated and implemented by product/service groups (or IPTs). The concepts of the multi-product adoption model can also be extended to alternative optimization contexts such as balancing profitability and market share with socio-economic responsibility.

Conclusion

Successful product development efforts during this phase of rapid and dramatic change in the aerospace and electronics industries requires technology leaders and corporate decision makers with the vision to pro-actively redirect strategies and dynamically allocate resources to remain competitive in today's global marketplace. Dual-use technologies and innovative technology transfer complemented by an eventual convergence of commercial best practices and military standards can catalyze the tremendous cultural change necessary to gain cost efficiencies and maintain the United States as a technology development world leader. Organizational restructuring and process reengineering must not neglect to recognize the elements of an existing system which have supported the proven successful development of core enabling technologies in the United States in the past.

SUMMARY OF THESIS RESEARCH AND SUPPORTING ANALYSIS

As indicated in the Executive Summary, technology demands for the aerospace and electronics industries will continue to change based on dynamics in the global economy. The research findings presented in the Executive Summary outlined six basic areas repeated below as items (A.) through (F.). Items (E.) and (F.) have already been introduced. In this section, a basic description of the findings in items (A.) through (D.) is given.

A. Aerospace and electronics industries have evolved considerably due to external factors.
B. Organizations are rapidly responding and adapting appropriately to market forces.
C. Continued change is required on two fronts—technical redirection and strategic policy.
D. Management of these changes causes stress across intra-organizational boundaries.
E. Improved efficiency is achievable through the multi-product adoption model.
F. Efficiencies from multi-product adoption strategy and tool set are scalable.

A. Aerospace and electronics industries have evolved considerably due to external factors.

1. *New World Order*

Since the end of the Cold War, emphasis of U.S. defense technology has shifted to a model reminiscent of commercial markets, where cost is a significant parameter in the equation governing product success. The security that cost-plus contracts provided in the past to fund high technology research and development has been reallocated to a more equitable sharing of cost and risk between customer and contractor. This paradigm shift forces movement toward leaner and more agile process-centered business practices for defense prime contractors.

> *In today's post-Cold War world, the United States no longer faces a single galvanizing threat such as the former Soviet Union. Instead, there is increased likelihood of our forces being committed to limited regional military actions—coalition operations—in which allies are important partners... placing a high premium on interoperability ... and focusing on fielding superior operational capability and reducing weapon system life cycle costs [42].*
>
> Dr. Paul G. Kaminski
> Under Secretary of Defense for Acquisition and Technology

2. *Market Consolidation*

U.S. aerospace and electronics companies are experiencing a period of widespread mergers and acquisitions. The inevitable result of these consolidations for efficiency is a reduction in the labor force. For existing players, those which survive the drastic cutbacks in defense spending will ultimately find U.S. defense procurement moderately attractive, with a nearly monopolistic structure to remain when the industry eventually experiences the next growth phase.

B. Organizations are rapidly responding and adapting appropriately to market forces.

1. *Mergers and Acquisitions*

The mergers and acquisitions period is bringing greater efficiency to business operations in the defense sector through a movement toward "right-sizing" the labor force and pro-active alignment of operations to the changing needs of the customer. Consolidation of operations and a focus on integrating distinctive complementary core competencies under one roof brings greater affordability to new product development to meet evolving needs in the defense sector.

The trend toward greater internationalization of aerospace marketing and production will continue through acquisitions abroad by U.S. companies and partnerships with foreign manufacturers. Such arrangements offer the advantages of cost and technology sharing, bearing in mind that the U.S. is no longer sole custodian of the world's aerospace technology. But there is an even greater advantage: Teaming with a foreign partner can provide access to a market that might otherwise be closed to the American company. It is an economic fact of life that 50% of something is better than 100% of nothing [18].

Don Fuqua, Aerospace Industries Association (AIA) President

2. *Process Reengineering and Organizational Restructuring*
   Emphasis on product life cycle cost has triggered adoption of many commercial best practices by defense contracting organizations. Examples of these best practices include lean and flexible manufacturing, design for six sigma, and platform-based design. Organizational restructuring to models which support integrated product design and facilitate vertical partnering continue to make major improvements in operational efficiency at many firms.

3. *Leveraging of the National Industrial Base*
   Over the past several decades, global competition in the commercial sectors for high technology industries has resulted in a strong U.S. national industrial base. Commercial technologies such as high throughput microprocessors and high density data storage devices which are suitable for incorporation in military systems have induced major acquisition reform and a streamlining of U.S. military standards. As a result, significant second order market force effects will continue to emerge in the commercial sector based on the increasing level of demand for commercial technology insertion in future military systems.

C. Continued change is required on two fronts—technical redirection and strategic policy.

1. *Technical Redirection*
   Technologies required to maintain U.S. national security are shifting to greater emphasis on surveillance and information systems, creating a segment of relative growth in an otherwise downsizing industry. Because substantial commercial market demand exists for such enabling technologies as advanced image compression and high bandwidth wireless telecommunications, there is a natural desire to develop these and others as dual-use enabling technologies. A one-target one-weapon policy has become the goal of defense technology development with a focus on precision-guided weaponry and electronic warfare supported by advanced sensors and an elaborate information system infrastructure.

Today, we must cope with an expanded range of ambiguous threats. The coming decades promise a quantum shift in the evolution of armed conflict. We are moving to a situation of one target one weapon. One of the key pillars of the revolution is the need to achieve something called "dominant battlefield awareness." It means knowing everything going on in a battlefield... much more than knowing the static location of forces. Commanders will need to know the combat readiness status or "state vector" for each force element [40].

Dr. Paul G. Kaminski
Under Secretary of Defense for Acquisition and Technology

2. *Strategic Policy*
   Massive labor force consolidation, especially in manufacturing and mid-level management in U.S. aerospace and electronic firms, has led to stress and cynicism among many remaining employees, and animosity among many of those who have been forced out. A necessary future

strategic policy change includes maintaining a well-trained work force by encouraging, if not forcing, employees to gain transferable and portable skill sets. Management of the change to the new model process-centered organization must shape industrial culture by blending the strengths of "new school" and "old school" philosophies, educating all employees in all significant aspects of product development and business management processes.

> *"It's not my job" is the most commonly heard phrase in a traditional company. In a process-centered company, nobody says that. Even if they're not doing all the tasks, they understand them all [33].*
>
> Michael Hammer, President of Hammer and Company
> Co-author of "Reengineering the Corporation" (1990s best-seller)

D. Management of these changes causes stress across intra-organizational boundaries.
As organizations continue to consolidate operations and adjust corporate strategies to align with the changes in future technology needs, massive labor force reductions and major organizational restructuring has left many employees with perceptions of reduced career growth opportunities. This situation can lead to morale problems throughout almost all organizational levels. From the rank and file up through mid-level management, even the most capable engineers and managers see fewer growth opportunities as organizations become flatter, flexible, and more networked to meet the challenges of today's truly global business environment.

For those employees who do continue along career paths with strong steady growth, the situation is still perceived as less than optimal. Incentive systems which have traditionally relied on percentage-based annual salary increases linked to employee performance assessments can no longer maintain the levels which were commonplace during the high inflation period of the 1980s. Retirement incentive packages have forced many highly experienced employees to be replaced by a new generation of highly capable younger leaders, a generation which has assumed all of the responsibility and accountability but has generally not been awarded the premium salaries commanded by many of their predecessors. As a result, dichotomous schools of thought have emerged, segmented largely along boundaries of age and experience with tension stemming from policies for allocating a very modest annual raise pool.

Identification of root causes for the resulting morale problems leads to a solution which parallels the model most organizations are adopting for their production operations. As with the movement to flexible manufacturing and platform-based design for products, employees must too be given transferable skill sets and portable competencies which are modular and compatible across multiple career applications to ensure that their value will continue to grow independent of market forces in a single industry. Giving employees transferable skills also increases corporate flexibility.

General Conclusions
Research for this thesis reveals that in the aerospace and electronics industries are experiencing a major transition to increased cost efficiency through product-dedicated design team practices. This transition is due in large part to the evolutionary global economic changes resulting from the end of the Cold War. In the movement toward new business models characterized by integrated product and process design teams, this thesis identifies key areas for continued change and strategies for sustainable growth based on the development of dual-use core enabling technologies. The multi-product adoption model and tool set are posed as a candidate approach for affordably meeting the changing technology demands of this highly dynamic era.

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CHAPTER 1. MOVING FORWARD BY UNDERSTANDING THE PAST

1. INTRODUCTION

1.1 Motivation for Thesis

Motivation for this thesis comes from a recognition of the impact that the substantial changes in the world economy continue to have on the technology demands for the next generation of products in defense and commercial markets, particularly in the aerospace and electronics industries in the United States. Because advanced technology products require extensive development time and major financial commitment, a tremendous amount of research has been dedicated in recent years toward achieving improvements in life cycle affordability for complex products. In order to remain successful, companies that develop high technology products must be responsive to the changes in customer needs and values as the United States transitions from a manufacturing-based economy to a knowledge-based economy in the global marketplace.

A comprehensive investigation of the recent dynamics in the aerospace and electronics industries reveals a movement toward the development of **dual-use technologies** and **structured system engineering best practices** in response to the increasing demand for reduced life cycle costs and accelerated product development. For aerospace and electronics, the massive financial backing of the U.S. Department of Defense (DoD) exerts significant influence in directing technology evolution and in steering the development of enabling critical technologies for future product applications. In response to the changes in technologies needed to maintain national security and sustain military superiority, there have been major structural modifications to U.S. Government procurement practices and policies for funding scientific research. A second order effect of these defense sector market forces results in significant impact to the commercial sector as well.

As a result of today's post-Cold War military environment, the U.S. defense business strategy, force structure, and infrastructure have been reformed to align with a very different set of needs than those of recent past history. Prior to the end of the Cold War, the Soviet Union was intact and held significant military and economic power, creating a situation in which technical superiority was the primary goal of United States defense initiatives. In addition, U.S. intelligence information helped to form an environment in which the technical capability of the opposition was in large part known and was evolving at a reasonably predictable pace. Since the downfall of Soviet power and divergence of the Soviet republics, emphasis of U.S. defense technology has shifted to a model more reminiscent of commercial markets, where cost is a significant parameter in the equation governing product success. Today's maintained U.S. security is manifested in the ability to defend against much smaller scale conflicts with higher uncertainty and more variability, requiring rapidly deployable assets and cost-effective high precision technology. As indicated in Exhibit 1.1-1, the end of the Cold War marks a major redirection of U.S. defense technology development.

Sustaining Flight Through the Power of Knowledge [42]

Ira C. Eaker Distinguished Lecture on National Defense Policy
Address of The Under Secretary of Defense for Acquisition and Technology
Dr. Paul G. Kaminski
to the United States Air Force Academy
May 2, 1996

America's armed forces are going through a dramatic transformation—everything from objectives and strategy to weapons and force structure to doctrine and tactics. The world is changing, and just like the larger civilian society that we protect and serve, so to must we adapt to the changes driven by the information revolution. In the post-Cold War world, the United States no longer faces a single galvanizing threat such as the former Soviet Union. Instead, there is increased likelihood of our forces being committed to limited regional military actions—coalition operations—in which allies are important partners. Deploying forces in coalition operations with the forces of other countries places a **high premium on interoperability**—that is, ensuring that U.S. and allied systems are compatible and can be sustained through a common logistics support structure.

I would sum up our current national security in statistical terms by saying that the **mean value** of our single greatest threat is considerably reduced. But the irony of the situation is that the **variance** of the collective threat that we must deal with, and plan for, and must counter is up. This gives us some pause in trying to plan intelligently. In response to reduced mean value of the threat, the United States has cut end strength by about a third from 1985 levels. But at the same time, the increase in variance has caused deployments of U.S. forces to go up by a third. In the defense acquisition and technology program, this means we are focusing on fielding superior operational capability and **reducing system life cycle costs.**

A chess analogy is useful for explaining what this means for the changing nature of warfare. Today, precision weapons have now made it possible to take any piece on any square of the chessboard with no collateral damage to adjacent squares. Given this **one target one weapon** capability, commanders now need to know where all one's forces are and where all the targets are on a 100 x 200 kilometer battlefield. This is analogous to seeing all the pieces on the chessboard—something we take for granted when playing chess. Imagine how fast you would win the game if you could see all the pieces on the board, but your opponent could see only his major pieces plus a few of your pawns. This is what is meant to have **Dominant Battlefield Awareness**. To secure an overwhelming advantage, commanders will need C^3 (Command, Communications, and Control) and planning tools to achieve something I call **Dominant Battle Cycle Time**—or the ability to act before an adversary can react. Back to the chess analogy, dominant battle cycle time would be, well, gaining an unfair advantage by breaking the rules—it means to keep moving your pieces without giving your opponent a chance to move his.

Exhibit 1.1-1: United States Defense Technology Redirection

As the United States transitions into the next century, two conclusions can be drawn from the recent reports and press releases from the U.S. DoD. First, there is an unprecedented emphasis on reducing life cycle costs for next generation defense systems. No longer is it sufficient to rely solely on technological superiority in order to compete effectively in the defense sector in the United States. Affordability has emerged as the driving parameter in maintaining market share through new contract awards in a period of shrinking defense procurement and research funding. Second, probably the largest relative growth segment of defense research, development, and procurement for the near future involves information technologies such as integrated surveillance systems and optimized battlefield command, communication, and control (C^3). Surveillance system technologies are a natural fit to the dual-use strategy of multi-product adoption as presented in this thesis. These technologies include both the design of the hardware and enabling components as well as the development of very large scale software systems to support automation and operation.

The significance of these evolutionary changes in the development of enabling technologies for defense systems is that there is a substantial second order effect which impacts the commercial side of the aerospace and electronics industries in the United States. Recognizing the gains in efficiency made by commercial companies in such technology-driven industries as automobiles, aircraft, and microprocessors, the United States DoD procurement practices are undergoing revolutionary reform characterized by a streamlining of military standards and an adoption of many commercially proven best practices. This attempt to leverage the strengths of a highly effective U.S. commercial industrial base has introduced the opportunity for increasing use of commercial-off-the-shelf (COTS) components in new military system designs. As a result, the competitive playing field for the aerospace and electronics industries has changed slope and the traditional distinction of defense versus commercial business continues to diminish.

Common manufacturing lines share the responsibility of producing components for a wider range of end products—commercial and military. Information technologies provide the infrastructure to facilitate efficiencies from subcontractor vertical partnering. Firms can leverage emerging capabilities to achieve greater economies of scale while simultaneously sharing fixed capital investment and equipment costs across a wider spectrum of end products. The crux of this thesis is to identify how an understanding of these realizable production efficiencies can be valuable in guiding decisions for the conception and development of future enabling technologies.

1.2 Scope

The scope of this thesis begins with an industry-wide analysis of the impact that recent changes in world order have made on the technology demands for next generation aerospace and electronics products. Increasing levels of detail are presented by stepping the focus down from global economics to U.S. Government initiatives, then finally to a single company's strategic response to the evolutionary changes. A strategic multi-product adoption model is introduced in Chapter 3 based on a set of guiding principles and best practices for the successful design and architecting of complex technological systems. Particular emphasis is placed on the facilitated development of dual-use enabling technologies and the encouraged use of multiple market insertion to gain scalable production efficiencies for core technology components. The model strategy attempts to address the challenges of defense spending reductions through the development of innovative dual-use technologies and increased international partnerships. Optimized supply chain management, leveraging of existing customer types, and full utilization of established distribution networks are discussed with respect to the multi-product adoption strategy. Extension of multi-product adoption concepts is applied to corporate-level decisions for balancing short-term and long-term trade-offs.

The multi-product adoption strategy elements attempt to illustrate the significance of finding an optimal balance between achieving exceptionally high technical performance and meeting specific cost targets. A fundamental element of the model is an emphasis on accurate and credible identification, quantification, estimation, and prediction of costs, risks, and schedule milestones. Cost efficiencies are sought at every level of product design, forcing engineers to be responsible and accountable for the economic consequences of their decisions. Streamlined military standards and encouraged adoption of world-class accepted commercial quality standards such as the ISO 9000 series marks the beginning of the evolutionary convergence toward a single military and commercial set of accepted best practices. Recognizing the product design and cost-efficiency benefits of integrated product teams (IPTs), this thesis investigates the potential parasitic effects that an over-restructuring to IPTs can cause on the elemental technology development process.

1.3 Introduction to Thesis Chapters

Chapter 1 serves as the thesis introduction, establishes the motivation and scope, and provides a definition of terms.

Chapter 2 presents a comprehensive aerospace and electronics industry analysis used to provide supporting data for establishing the merits of the multi-product adoption model presented in Chapter 3. A case study analysis of Raytheon Company, a firm which has achieved a successful balance of defense and commercial operations, provides a glimpse into one organization's actions in response to the changing climate of the new world order.

Chapter 3 introduces and describes the multi-product adoption model as an analysis framework and set of flexible guidelines for achieving sustainable competitive advantage in today's high technology industries. Consideration is given to the significance of strategically building from proven core competencies and exploiting existing customer types, marketing channels, and distribution networks in optimizing the probability of successful new market penetration. Further discussion includes identifying and meeting latent needs of customers with entirely new technologies which present unknown beneficial value in revolutionary new products.

Chapter 4 concludes with a corporate level abstraction of the multi-product adoption model. The issue of balancing profitability and market share with socio-economic responsibility is discussed. A brief summary is presented which outlines a distinction between attaining multi-industry competitive advantage for sustainable growth through multi-product adoption versus basic product diversification through conventional portfolio management.

1.4 Definition of Terms

This section presents a consolidated set of the terminology used in developing the concepts in this thesis. These terms are defined here for the specific context used in this thesis and are listed roughly in their respective order of appearance from the main body of the document.

Core Technology Development Teams (CTDTs)

A distinction is made in this thesis between CTDTs and integrated product teams (IPTs). The distinction is significant and is a fundamental part of the multi-product adoption model. CTDTs represent a central element for continuing revolutionary growth in the development of enabling technologies. In contrast with IPTs, CTDTs should very rarely be dedicated to a single product. CTDTs act as the supplier to IPTs—providing value added through development of dual-use enabling technologies and delivering technologies to IPTs for product insertion. In the examples used in this thesis, the technologies are the underlying components, devices, subassemblies, or processes, which combine to create the final product application. The role of CTDTs is to develop technologies to a production-ready state, and to promote multiple market insertion.

Integrated Product Teams (IPTs)

IPTs are the internal "customers" or "users" of core technologies developed by CTDTs within an organization. IPTs are generally dedicated to a single product or family of related platform-based products. They represent the customer-focused implementation arm of a company, the strategic mechanism by which core enabling technologies become end-user products. In the multi-product adoption concept presented in this thesis, IPT members periodically rotate into CTDTs and are encouraged to provide directive interaction for the CTDT efforts.

Defense Sector

This thesis defines the defense sector as the collective set of business transactions between contractors and the United States Government for end-use products designed to maintain national security. Specifically, defense sector products and technologies are those which have primary use in military applications. The defense sector also includes foreign sales of military technology products.

Commercial Sector

The commercial sector is the collective set of business transactions which do not include the procurement of military weapons by the U.S. Government or any foreign party.

Multi-Product Adoption Model

The multi-product adoption model is the term used to describe the analysis framework and operational guidelines introduced in Chapter 3 of this thesis. The main objective of the multi-product technology model is to provide a mechanism for promoting the development of dual-use technologies and catalyze the transfer of technologies including product commercialization.

Competitive Advantage

When a firm performs considerably better than average in an industry, it usually has some special feature, capability, or property which is difficult to imitate that allows it to out-perform its rivals. Michael Porter refers to such assets as competitive advantage [65,69]. This term has become common in strategic management to describe the benefit of acquiring distinctive competencies which provide an edge over competing firms in an industry.

Dual-Use Technologies

Dual-use technologies are generically defined to be those enabling devices or technical processes which are suitable for multiple market insertion across defense and commercial product lines. Examples of dual-use technologies presented in this thesis are optimal robust real-time multivariable control and advanced radar and infrared sensor systems. The product applications for such technologies have found demand in commercial and defense markets such as missiles, surveillance systems, automated highway, air traffic control, and medical ailment diagnosis. Note that the full scope of dual-use technologies and product applications extend far beyond the few examples presented in this thesis.

Technology Transfer

Technology transfer is a term used to describe the process of inserting specialized technologies, usually developed to meet a specific or unique requirement, into new and diverse product applications. Often this process results in developing new markets and relies on meeting the latent needs of customers in emerging markets. Examples of technology transfer may include such products as commercial global positioning systems in automobiles, or wireless telecommunications for residential use such as the capability presented by the Internet and world wide web.

Product Commercialization

Product commercialization is similar to technology transfer. Products which have been developed to meet one set of customer needs (typically military) can often find emerging markets in the commercial sector with minimal tailoring or repackaging. For example, thermographic cameras which house infrared focal plane arrays (IR FPAs) developed for military target tracking systems and space exploration by NASA have recently also found market demand as medical screening instruments, components in automated thermal signature access systems, and high fidelity bridge fault inspection devices.

Vertical Partnering

Establishing value-added subcontractor or supplier relations as a strategic means of gaining competitive advantage is often referred to as vertical partnering. In contrast, horizontal partnering would be an appropriate term to describe the situation where two peer companies decide to form a cooperative partnership to compete more effectively against a common third competitor.

ManTech

The ManTech initiative is a "Manufacturing Technology" program under the direction of the United States Department of the Air Force with a mission to identify key cost-savings areas for streamlining with a focus on subcontractor-related processes and supply chain management. Specifically, ManTech searches for processes which can be made more cost-efficient by using computer-aided design/manufacturing/engineering (CAD/CAM/CAE) resources and centralized integrated product design databases.

Affordable Multi-Missile Manufacturing (AM^3) Program

The AM^3 Program is an Advanced Technology Demonstration (ATD) project sponsored by ARPA. The objective of the program is to demonstrate advanced missile design and manufacturing concepts for the future incorporation of systems which can substantially reduce the cost of United States DoD procurement and research for advanced technology defense systems.

Balanced 360-Degree Product-Technology Integration Philosophy

This term is introduced as one of the elements of the strategy for multi-product adoption. It refers to a system design and management perspective which takes into account more than a single product or technology. The suggestion of this aspect of the multi-product adoption model is that there is an optimal balance between developing new products with new technologies and upgrading existing products with the insertion of new technologies. The proper balance of objectives should be maintained to mitigate the technical, cost, and schedule risks of developing next generation high-tech products.

Porter's 5-Forces Analysis

A powerful strategic management analysis model has become standard practice in assessing the attractiveness of the current state of an industry. This model can be used to comprehensively analyze industries from the perspective of five distinct forces—competitive rivalry, buyers, suppliers, substitute products, and barriers to entry. The model was first introduced by Michael Porter in the 1980s [69] and has gained wide acceptance in the strategic management community for analyzing almost any industry.

Cross-Functional Integrated Design (CFID)

CFID is Boeing's new process prototyping concept which can be used to assist managers of complex engineering projects to "design the design process." The CFID concept is a departure from traditional function-driven design, resulting in a data-driven reengineered design process which has been shown to yield greater cost efficiency over conventional methods in the design, development, and production of commercial aircraft.

Massachusetts Economic Situation

The Massachusetts Economic Situation, as used in this thesis, is phrase coined by Raytheon executives to describe the competitive pressures of maintaining defense manufacturing operations in Massachusetts during the significant decline in U.S. Department of Defense spending. By 1995, in order to escape the burden of operating in other high cost states, many of Raytheon's principal competitors in the defense electronics business segment moved to states offering lower cost operations through tax-based incentive programs designed for attracting manufacturing enterprises.

Technology Reinvestment Project

The Technology Reinvestment Project, sponsored by the Advanced Research Projects Agency (ARPA), is a unique virtual organization which spreads across many agencies and offices in the United States Government. Its central mission is to stimulate a merging of defense and commercial industrial bases to assure Department of Defense access to critical defense-related technologies at a cost kept low though simultaneous commercial interest.

Parametric Cost Estimation

Parametric cost estimation is a methodology which develops and uses mathematical expressions relating cost as the dependent variable to one or more independent cost driving variables. These relationships are generally referred to as cost estimating relationships, or CERs. Although these techniques treat cost as a dependent variable, they are not necessarily in conflict with the school of thought to incorporate cost into the design process as an independent variable.

Cost as an Independent Variable (CAIV)

CAIV means making technical performance capability and development/production schedule a function of available (budgeted) resources. CAIV does not mean trading cost, performance, and schedule equally, but rather picking the correct affordable cost goal and sticking to it. If the true customer needs cannot be met after exhausting the design trade space, then the program must either revisit the budget allocations and raise the cost targets, or be canceled as unaffordable [41,63].

Activity-Based Costing

Activity Based Costing (ABC) is a departure from traditional cost tracking and estimating techniques. The ABC approach avoids lump summing general administrative and overhead costs as fixed uniformly distributed costs across an organization. ABC attempts to track costs more accurately in order to more precisely identify inefficiencies in a system.

Integrated Master Plan & Integrated Master Schedule (IMP/IMS)

IMP/IMS is a comprehensive milestone-driven system tool which integrates all significant aspects of a project in an attempt to ensure greater coherency in design and production. The detail of this tool, when constructed properly, is sufficient to replace the traditional work breakdown structure associated with engineering design projects. The IMP/IMS must include expected values for availability of specialty test equipment or long lead items from key suppliers. Early notification of schedule/plan deviations maximizes the recovery solution space for program managers and project engineers when program events do not meet planned/scheduled completion milestones.

Design for Manufacturing & Assembly (DFM/DFA)

Design for manufacturing and assembly represent two particular aspects of the "design for ..." family. The significance of DFM/DFA has emerged rapidly since the introduction of quantifiable and traceable structured methods and metrics by Boothroyd and Dewhurst [6,7]. The DFA index, as it is often referred, presents a powerful producibility metric for determining the relative ease of assembly for key components, inherently and continuously identifying areas or design features most suitable for relative improvement.

Quality Function Deployment (QFD)

QFD and the House of Quality [11,12,34] provides a structured process of incorporating customer values directly into the system engineering design process. The deployment of system requirements is driven by a series of matrices which develop a flowdown of top-level customer values and product attributes through detailed engineering specifications on subassemblies and components.

Design of Experiments

Taguchi methods for robust design provide a structured process for optimizing efficiency for experimentation using principles of signal-to-noise ratios and quadratic loss functions. The Design of Experiments methodology exploits properties of linear spaces and employs confounding to achieve systematic analysis to minimize total cost.

Design for Six Sigma

Design for Six Sigma has grown out of Motorola's "Quality Renewal Process" initiative [60] to achieve measurable improvements in customer satisfaction. By setting manufacturing specifications which target the variability in component tolerances, systemic improvements are achievable in producing components which are compatible with each other. Assuming Gaussian probability density functions as a model for the yield characteristics of manufactured components, standard deviations can be used as a metric for improvement. As variation decreases, capability increases, and consequently, the standard deviation is reduced. As a result, the probability of a defect is decreased and component reliability goes up.

Platform-Based Design

Platform-based design implies that a large percentage of core components in a particular product are shared across a family of products. By sharing components across multiple product lines, efficiencies are gained in terms of economies of scale at the component level, and efficiencies are facilitated at the assembly level through production balancing and reduced setup costs. The concept of platform-based design has roots in the Japanese automotive and electronics industries.

Supply Chain Management

Supply chain management provides a natural formulation for multidimensional optimization. Coordinating issues for constructing an optimal supply chain policy include balancing of many resources and operation choices. Examples include outsourcing versus vertical integration; choosing between alternative supply sources, technologies, and equipment; scheduling production activity; plant loading and location of plants and distribution centers; inventory positioning and holding levels; and, vehicle routing and crew scheduling [52]. Optimization can be applied on multiple levels—operations, tactical planning, and strategic planning.

Material Requirements Planning (MRP)

MRP is a means of converting (forecasted) demand for a final product into a requirements schedule for the various components comprising that product, accounting for variability in demand and across multi-stage production processing times. Using this requirements schedule, a complete production plan including order select sheets and weekly promise sheets can be constructed for a given finite planning horizon [61].

Just-in-Time (JIT)

JIT is a philosophy that grew out of a Japanese approach to organizing manufacturing operations, originally intended to gain cost-efficiency in moving material through a plant. The core element of the JIT philosophy is to eliminate waste. JIT uses small frequent deliveries from a few selected suppliers based on long term negotiated prices and purchasing agreements. Geographic proximity promotes frequent communication and information exchange in order to gain cost advantages over conventional purchasing procedures [61].

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CHAPTER 2. INDUSTRY ANALYSIS

2. AEROSPACE AND ELECTRONICS INDUSTRY ANALYSIS

From a broad perspective aerospace and electronics represent two diverse industries. For the purposes of this thesis, the intersection of these two industries is treated collectively as a single dynamic entity with reasonably stable product boundaries which include such complex systems as guided military weapons, wide area surveillance, commercial air traffic control, personal rapid transit, advanced radar and infrared sensor technology, wireless telecommunications, satellite technology, global positioning systems, and the associated requirements, planning, algorithm development, and software and hardware realizations to house and support these technological products.

2.1 Key Industry Trends

This section begins with a detailed analysis of the United States defense industry, specifically the U.S. Department of Defense (DoD) research and development and procurement budget histories, followed by discussion of expected changes in customer needs for the defense system technologies in the near future. A Porter's Five Forces strategic management analysis model is constructed to serve as a fundamental framework for understanding the present state of defense contracting in the United States. Reports, statements, and press releases from the DoD agencies and the Office of the Undersecretary of Defense for Acquisition and Technology provide insight into the expected near-term future defense system technology customer needs. Next, an analysis of recent trends in the commercial side of the aerospace and electronics industries is presented, including a comparative assessment of the United States and Japan in electronics manufacturing and optoelectronic systems development. Movement toward the development of dual-use technologies and the development of strategic initiatives for innovative technology transfer are used as a basis for modeling the present state and future direction of the aerospace and electronics industries in the United States, for both the commercial and defense sectors of the market.

A cross-reference matrix of critical technologies based on sources of demand is presented in Exhibit 2.1-1. Analysis of the demand for technologies reveals a direction for expected growth for industry. By selecting complementary technologies, companies can gain competitive advantage through developing diverse products in multiple market segments which share common core technological components. By recognizing a company's core competencies and strategically aligning investments in selective technologies which have known demand, probability of successful product development is increased. For example, a company with a core competence in designing military target tracking systems might invest resources to develop enabling technologies in state-of-the-art sensor devices, high throughput computing, and advanced signal processing. Revolutionary growth in these core technologies could then be leveraged to expand product applications to include air traffic control, wide area surveillance, or access recognition systems.

Critical Technologies	DoD Critical Technologies	NASA, CSTI, and Pathfinder Technologies	Technology Initiatives	AIA Key Technologies for the 1990s	R&DD Key Technical Thrusts
Software Producibility	●	●	●	●	●
Sensor Technology	●	●	●	●	●
Advanced Materials	●	●	●		●
High Performance Computing	●	●			●
System Analysis & Engineering	●	●	●		
Computational Physics	●	●	●		
Advanced Electronics	●		●		●
Artificial Intelligence	●	●	●		●
Robotics	●	●	●		●
Photonics	●	●			●
Signal Processing	●	●	●		●
Space Structures		●			
Data Fusion	●	●	●		
CIEM/Manufacturing			●		
Signature Control	●				●
Space Sciences		●			
Directed Energy	●				
Propulsion	●	●		●	
Space Power & Cond.		●			
Nuclear Effects					
Humans in Space		●			
Biotech. Material & Proc.	●	●			

Exhibit 2.1-1: Assessment of Enabling Technologies and Demanding Agencies

Source: MIT 16.870 Lecture Notes

2.1.1 The Defense Sector

2.1.1.1 United States Defense Spending History and Acquisition Strategy

Over the past four decades, defense procurement spending has been cyclical with a 0.7% sustained growth, most recently experiencing a period of severe decline. There is an expected leveling off over the next several years to approximately 60% of 1985 values [3]. In response to the market forces induced by the cutbacks in federal procurement, large defense contractors have adjusted through massive reductions in the labor force and fierce consolidation of operations. Refer to Exhibit 2.1.1.1-1. These labor force reductions have been coupled with engineering wage freezes, intense union negotiations, and major tax reform, leading to economic pressures in the surrounding communities and hardship for middle-class working families, even though many corporations have simultaneously achieved record level profits.

Exhibit 2.1.1.1-1: Labor Force Reductions in Major United States Defense Contractors

Company	1985	1990	1994
Raytheon	73,000	76,700	60,200
Lockheed	87,800	73,000	82,500 ('93)
Texas Instruments	77,872	70,318	56,333
General Dynamics	101,000	95,100	24,300
GM/Hughes (with GD)	120,000 (1989)	95,000	79,000
Loral	81,000	23,750	28,900
Martin Marietta	66,600	62,000	92,000

* Note: In 1994, Lockheed merged with Martin Marietta to produce the largest U.S. aerospace firm. In 1995 Lockheed Martin merged with Loral's defense electronics facilities creating a $30 billion aerospace and electronics giant. Massive consolidation of operations and work force continue in 1996.

Source: Company Annual Reports

As illustrated in Exhibit 2.1.1.1-2 and Exhibit 2.1.1.1-3, the time history of the United States defense spending profile is characterized by cyclic changes. This appears to be due to changes along two axes. First, there is variability in supply and demand which results in inventory buildup for fielded weapons. Military products typically have long life cycles, 10 to 20 years or more, depending on the particular system. The technologies housed in these products are characterized by much shorter life cycles, so the slightest over-capacity of fielded system inventory runs a risk of becoming obsolete. The second significant aspect which causes cyclic spending is the crisis nature of the situations where weapons are used has also become highly variable in recent times. As a result, fielded technology usage is largely random and highly influenced by external factors such as third world volatility or coalition armed force activity. Ultimately, a type of limit cycle appears between procurement and the ability to respond effectively with production. The solution for contractors seems to reside in accelerating product development times and reducing system life cycle costs while maintaining military superiority in terms of technology and intelligence.

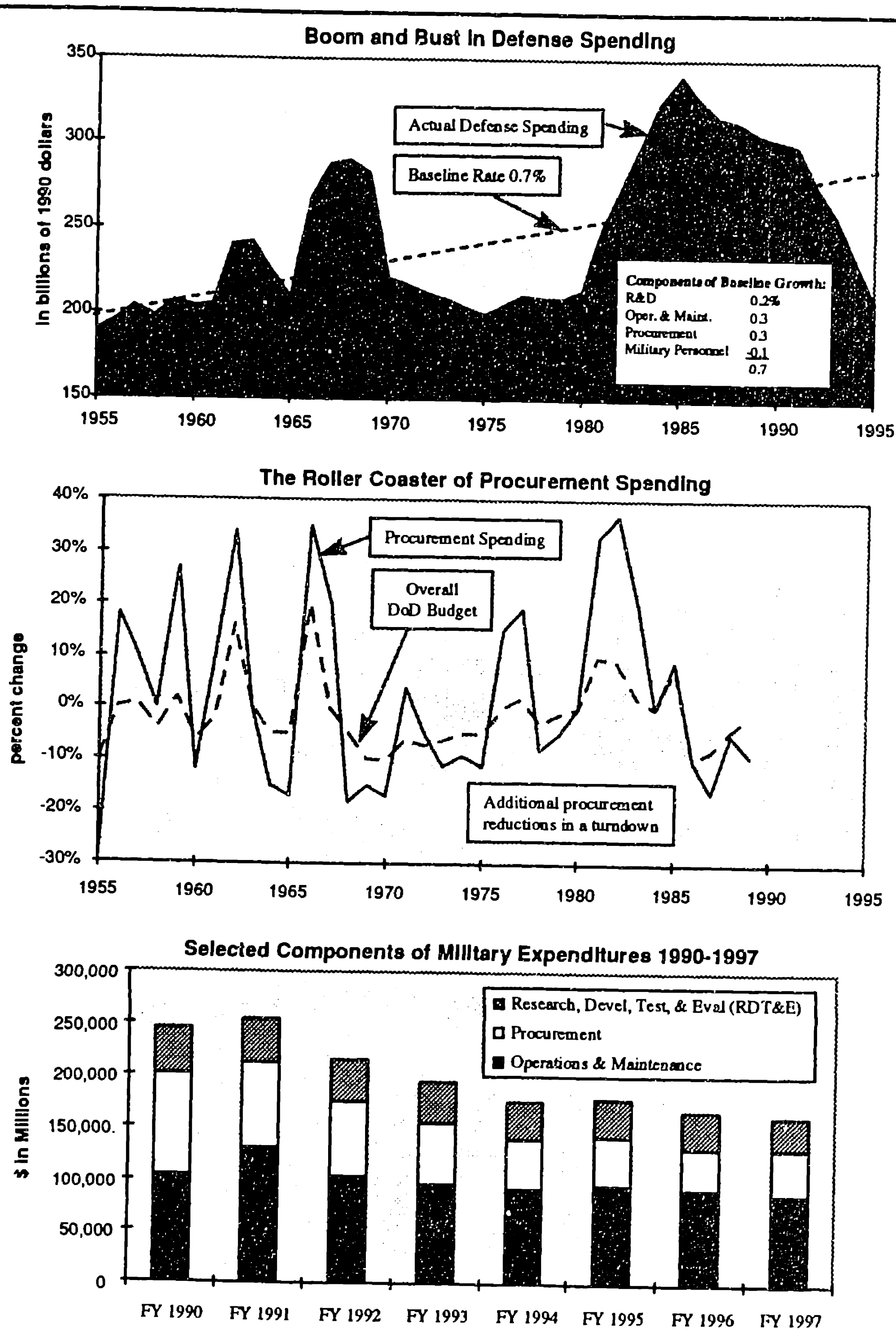


Exhibit 2.1.1.1-2: United States Department of Defense Spending History

Source: *Report from the Secretary of Defense to the President and Congress*, February 1995
Harvard business Review, November-December, 1992

Budget Tables
Department of Defense -- Budget Authority Appropriation (a)
(Dollars in Millions)

	FY1990	FY 1991 (b)	FY 1992 (b)	FY 1993	FY 1994	FY 1995	FY 1996	FY 1997
Current Dollars								
Military Personnel	$ 78,876.00	$ 84,213.00	$ 81,221.00	$ 75,974.00	$ 71,366.00	$ 70,595.00	$ 68,697.00	$ 67,492.00
Operations & Maintenance	$ 88,309.00	$ 117,234.00	$ 93,791.00	$ 89,172.00	$ 88,341.00	$ 94,381.00	$ 91,932.00	$ 90,590.00
Procurement	$ 81,376.00	$ 71,740.00	$ 62,952.00	$ 52,789.00	$ 44,141.00	$ 44,619.00	$ 39,409.00	$ 43,464.00
Research, Devel, Test, & Eval (RDT&E)	$ 36,459.00	$ 36,193.00	$ 36,623.00	$ 37,974.00	$ 34,567.00	$ 35,438.00	$ 34,332.00	$ 32,654.00
Military Construction	$ 5,130.00	$ 5,188.00	$ 5,254.00	$ 4,554.00	$ 6,009.00	$ 5,491.00	$ 6,573.00	$ 4,488.00
Family Housing	$ 3,143.00	$ 3,296.00	$ 3,738.00	$ 3,941.00	$ 3,501.00	$ 3,387.00	$ 4,125.00	$ 4,335.00
Defense-Wide Contingency						$ (703.00)	$ (72.00)	$ (30.00)
Revolving and Management Funds	$ 566.00	$ 2,701.00	$ 4,587.00	$ 4,503.00	$ 4,354.00	$ 297.00	$ 1,703.00	$ 506.00
Trust & Receipts	$ (832.00)	$ (44,329.00)	$ (5,733.00)	$ (435.00)	$ (809.00)	$ (763.00)	$ (334.00)	$ (507.00)
Deduct, Intra-gov't Receipt	$ (27.00)	$ (29.00)	$ (550.00)	$ (1,069.00)	$ (104.00)	$ (124.00)	$ (369.00)	$ (184.00)
Total Current $	$ 292,999.00	$ 276,208.00	$ 281,883.00	$ 267,402.00	$ 251,364.00	$ 252,608.00	$ 245,995.00	$ 242,808.00
Constant FY 1996 Dollars								
Military Personnel	$ 95,393.00	$ 97,494.00	$ 91,332.00	$ 81,894.00	$ 75,028.00	$ 72,376.00	$ 68,697.00	$ 65,568.00
Operations & Maintenance	$ 105,965.00	$ 131,339.00	$ 104,197.00	$ 96,247.00	$ 92,877.00	$ 97,031.00	$ 91,932.00	$ 88,032.00
Procurement	$ 95,871.00	$ 82,156.00	$ 70,318.00	$ 57,503.00	$ 46,803.00	$ 45,957.00	$ 39,409.00	$ 42,198.00
Research, Devel, Test, & Eval (RDT&E)	$ 43,060.00	$ 41,263.00	$ 40,683.00	$ 41,189.00	$ 36,584.00	$ 36,486.00	$ 34,332.00	$ 31,706.00
Military Construction	$ 6,051.00	$ 5,952.00	$ 5,873.00	$ 4,961.00	$ 3,669.00	$ 5,64[illegible].00	$ 6,573.00	$ 4,358.00
Family Housing	$ 3,721.00	$ 3,739.00	$ 4,148.00	$ 4,271.00	$ 3,703.00	$ 3,489.00	$ 4,125.00	$ 4,210.00
Defense-Wide Contingency						$ (724.00)	$ (72.00)	$ (29.00)
Revolving and Management Funds	$ 672.00	$ 3,074.00	$ 5,075.00	$ 4,857.00	$ 4,598.00	$ 302.00	$ 1,703.00	$ 492.00
Trust & Receipts	$ (988.00)	$ (50,446.00)	$ (6,334.00)	$ (469.00)	$ (856.00)	$ (786.00)	$ (334.00)	$ (493.00)
Deduct, Intra-gov't Receipt	$ (32.00)	$ (33.00)	$ (608.00)	$ (1,154.00)	$ (111.00)	$ (128.00)	$ (369.00)	$ (179.00)
Total Constant $	$ 349,715.00	$ 314,537.00	$ 314,684.00	$ 289,299.00	$ 264,797.00	$ 259,695.00	$ 245,995.00	$ 235,863.00
% Real Growth								
Military Personnel	-1.0	2.2	-6.3	-10.3	-8.4	-3.5	-5.1	-4.6
Operations & Maintenance	-1.1	23.9	-20.7	-7.6	-3.7	4.6	-5.3	-4.3
Procurement	-0.8	-14.3	-14.4	-18.2	-18.6	-1.8	-14.3	7.1
Research, Devel, Test, & Eval (RDT&E)	-6.6	-4.2	-1.4	1.2	-11.2	-0.3	-5.9	-7.7
Military Construction	-13.7	-1.7	-1.3	-15.5	28.4	-11.4	16.5	-33.7
Family Housing	-7.5	0.5	11.0	3.0	-13.3	-5.8	18.2	2.0
Total %	-2.2	-10.1	0.0	-8.1	-8.5	-1.9	-5.3	-4.1

(a) Numbers may not add to totals due to rounding
(b) In FY 1991-92, abrupt increases in budget authority, especially in O&M were due to the incremental costs of Operation Desert Shield/Storm.
The FY 1991-92 sharp rise in receipts reflects offsetting allied contributions.

Original Source: Report from the Secretary of Defense, to the President and Congress, February 1995, Page D-1.

Figure 2.1.1.1-3: United Stated Department if Defense Budget Tables

There are five fundamental elements of the DoD strategy to maintain technical superiority in the development and acquisition of high technology defense systems while simultaneously achieving greater affordability and accelerated product development, refer to Exhibit 2.1.1.1-4 [3]. The implementation of these five initiatives has induced transient effects in industry characterized by consolidation of operations and scaling back of the skilled labor force throughout the United States aerospace and electronics industries.

Exhibit 2.1.1.1-4: United States Department of Defense Strategy Elements [3]

- **Right-Sizing of the Infrastructure:** Defense spending is expected to level off at approximately 60 percent of the 1985 budget appropriations.
- **Reduce Cost of Weapon System Ownership:** Emphasis on reduction of life cycle costs and total cost of ownership, not just unit production cost.
- **Acquisition Reform:** Streamlining of military standards, adoption of commercial best practices, and increased commonality of components to achieve cost efficiencies.
- **Leverage National Industrial Base:** Microprocessor technology, advanced composite materials, telecommunications, and software development are segments of the commercial industry that can be used to capture advantages for military products.
- **Leveraging Allies' Industrial Base:** Improvements in international cooperation for system compatibility are essential in meeting the demand for coalition operations.

Source: Ayoob, *Aerospace Defense Contracting in the 1990s*, August 1995

In order to provide insight into the operations of competing in the defense sector, it is valuable to understand the structure and organization of the main customer, the U.S. DoD. A top-level organizational structure of the U.S. DoD is illustrated in Exhibit 2.1.1.1-5. In addition to the four major divisions—the Army, Navy, Air Force, and Office of the Secretary of Defense—there are agencies staffed by business management specialists and service officers which are emerging as the decision makers for steering the next generation of defense technology development. Typical defense technology contract awards are categorized into one of several basic types—technology development and insertion, engineering manufacturing and development, low rate and full rate production, product maintenance and upgrades, and operation and training.

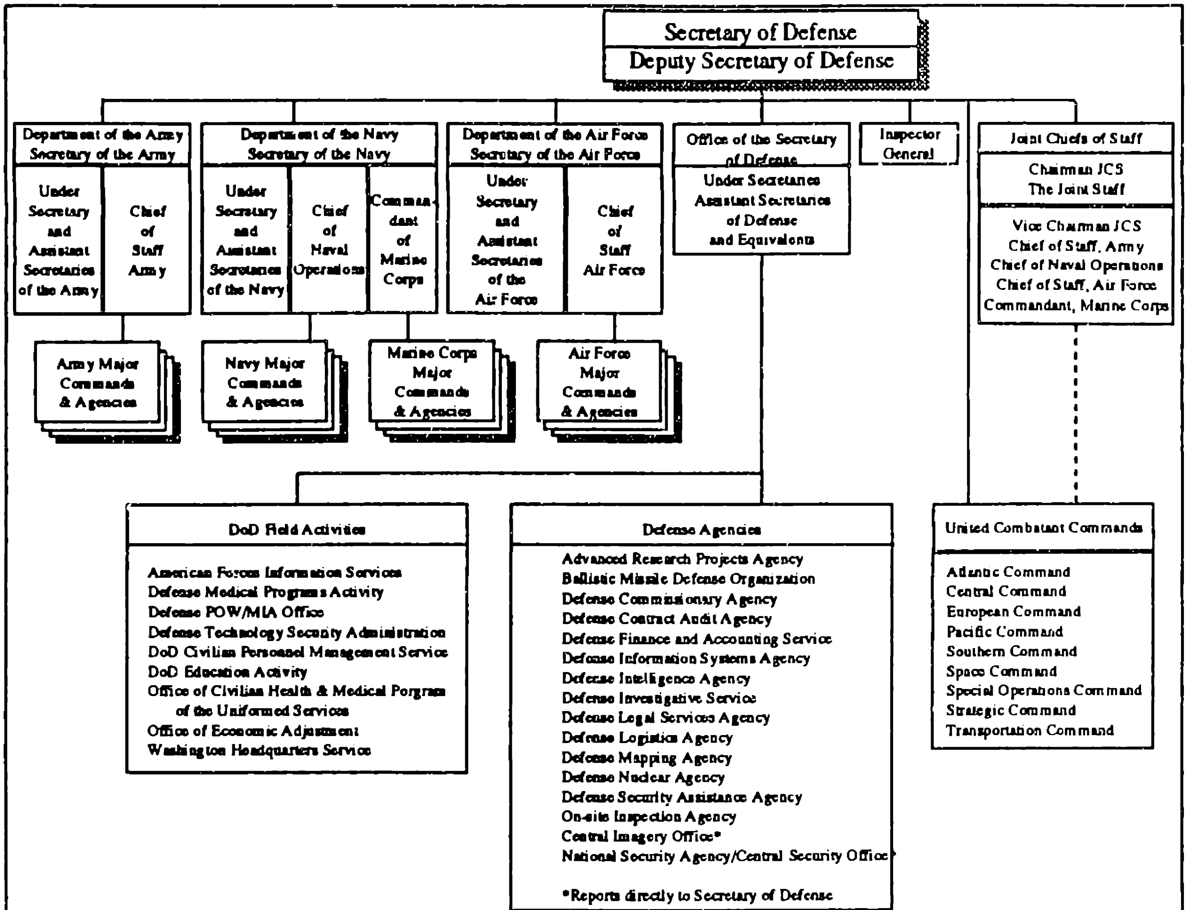


Figure 2.1.1.1-5: United States Department of Defense Organizational Structure

Source: *Report from the Secretary of Defense to the President and Congress*, February 1995

The Ballistic Missile Defense Organization (BMDO) is a DoD agency which emphasizes the U.S. theater missile defense (TMD) initiatives to meet the existing missile threat to deployed U.S. and allied forces, and to provide a hedge against the emergence of long-range ballistic missile threats. BMDO is empowered to manage research and production contracts with a focus on the ability to defend against the ballistic missile threat. Another DoD agency, the Advanced Research Projects Agency (ARPA), has the mission to develop imaginative, innovative, and often high-risk high-payoff research ideas offering a significant technological impact that will go well beyond the normal evolutionary development approaches. The ARPA mission is to pursue these revolutionary ideas from the demonstration of technical feasibility through the development of prototype systems.

Both ARPA and BMDO have some degree of control in steering the development of enabling technologies by virtue of their vested interest in producing highly effective electromechanical weapon systems. In order to gain an understanding of the characteristics of operating in the defense prime contracting industry in today's business environment, a Porter's Five Forces Model has been developed from the perspective of the contractors and is presented in Section 2.1.1.3. BMDO and ARPA are considered the "buyers" in the Five Force Analysis. A top-level overview of major contract types used in defense acquisition and procurement is given in Appendix 3.

2.1.1.2 Department of Defense Acquisition and Procurement Reform

In response to pressures to reduce defense spending in the U.S., the Department of Defense (DoD) has initiated significant changes toward institutionalizing the acquisition reform agenda. Moving from the conventional rule-based disciplined management approach for acquiring systems to meet military requirements, the DoD has recently adopted many of the tenets of business process reengineering which have proven to significantly reduce development cycle time and marketing costs in the commercial sector.

The U.S. DoD acquisition reform agenda includes a major revision of many military specifications, directives, and detailed instructions. A major rewrite of the Federal Acquisition Regulations (FAR) and Defense FAR Supplement along with several legally adopted initiatives such as the Federal Acquisition Streamlining Act (FASA) have marked the beginning of the end of an era of business practices which have proven inefficient in today's modern competitive economy. U.S. defense procurement practices are following suit by requiring contractors to operate in integrated product teams and permitting, even motivating, the extensive use of commercial off-the-shelf (COTS) technology components and non-developmental items (NDI). Many recent Requests for Proposal have tied a direct link between substantial contractual incentive and award fees to a contractor's ability to meet predicted target cost values.

2.1.1.3 Porter's Five Forces Model for Defense Prime Contracting

A Porter's Five Forces Industry Analysis Model [69] is often useful to assess the attractiveness of a particular industry. The Five Force Analysis provides a powerful framework for understanding the interactions among competitors, suppliers, buyers, substitute products or services, and barriers for new entrants. The general conclusion that can be drawn from the model presented in this section is that the current state of the aerospace and electronics defense contracting industry is rather unattractive, especially for new entrants. Initial investments are high and a key element of success is to have a previous history of proven high-quality on-schedule production capability. For the existing players, those which survive the drastic cutbacks in defense spending will ultimately find the industry moderately attractive, with a nearly monopolistic structure to remain when the industry eventually experiences the next growth phase [3]. Because electronic warfare technology is advancing so rapidly worldwide, including increases in threat capability, it is reasonable to expect that there will be eventual growth in new military weapon system procurement.

Competitive Rivalries

From the perspective of competitive rivalries, analysis indicates that for companies with intentions of continuing to compete in the defense sector, a strategic response to the evolutionary changes in world order and DoD procurement needs must include innovative measures for achieving cost efficiency. Due to the specialized nature of government procurement practices and the relatively complex technological development involved, defense systems have frequently offered higher unit contributions than many commercial products. Recent changes in customer needs have induced a period of increased competition and reduced profitability for many contractors. In turn, the industry is experiencing a phase of strategic mergers and acquisitions as major players jockey for position through product focus, complementary diversification, and consolidation of operations.

Suppliers

Suppliers to major defense contractors are vast in number and very diverse in size and scope relative to each other. Value chain control has generally been dominated by prime contractors who bring key technologies to product design and also provide the critical elements of system integration, test, and evaluation. The information revolution has introduced new mechanisms for reducing costs through innovative vertical partnering and strategic alliances between prime contractors and subcontractors allowing for equitable cost sharing among the major entities of the product value chain. Since prime contractors can leverage buying power to provide capital resources to support cost reductions through improvements in engineering services, this perspective suggests that the prime contractors hold more power than subcontractors and suppliers in developing, producing, and selling the final product to the end user. These issues indicate that the defense industry is moderately attractive for existing players with regard to supply chain management and control, as long as sufficient resources exist to remain competitive through the transition to drastically reduced defense spending levels.

Buyers

Buyers in this analysis represent the major procurement and research funding bodies in the United States DoD and foreign governments. In many instances, dual-use commercial avenues for defense technologies exist which also influence collective buyer power. Buyers have substantial control over steering the future of technology development and the purchase of products which house these technologies. The collective financial strength of buyers coupled with evolutionary changes in technology demands pose challenges to competing effectively in the aerospace and electronics industries, at least from the perspective of defense prime contracting. One strategic response to this situation is to explore the possible synergistic combinations offered by actively competing in both the commercial and defense sectors under the guidelines of the multi-product adoption model.

Substitutes

Influence of substitute products is relatively low since the industry is dominated by specialized products, long product life cycles, and many follow-on contracts and continual product generation upgrades. There is a high level of interaction among the forces presented by substitutes and rivalry of competition in the Five Force analysis because many companies choose to enter partnerships to avoid losing continued development of large scale projects. Even companies which are typically fierce competitors often choose to become allied partners on selective project ventures. These circumstances provide for a very unique corporate decision making structure and intensely competitive operating environment.

Barriers to Entry

Since the costs of doing business are extremely high, and because capital expenses required for research and development often do not yield significant payback until many years in the future, defense contracting is not generally attractive to new firms. In addition, fielded systems and inventory levels already are at capacity levels. Major procurement is dropping steadily and a focus has been developed for "build, demonstrate, and shelf" technologies. These contracts are not nearly as profitable in the long term as major procurement for production contracts. It often takes production contracts to recover the internal investments to develop a defense technology product. New entrants lacking established track records would have difficulty in diminishing a perceived risk in delivering production lots given the amount of resources required to actually build and test such large-scale systems. On a smaller scale, new competitors can enter the industry through the supply chain, specializing in required hardware or software and developing a niche in which to provide added value to a particular product. Actually, with the defense reform agenda presently underway, a door has been opened to commercial firms for integrating commercial-off-the-shelf (COTS) components into future military designs.

General Conclusions from the Porter Five Force Analysis

The current state of defense contracting is rather unattractive, especially for new entrants. Because the industry has faced significant downturn and is only beginning to approach leveling-off, existing players continue to maneuver for position in an environment which appears to be entering a type of maturity plateau. Due to the intense merger and acquisition process currently characterizing the industry, it is expected that as the market forces reach steady state equilibrium, industry control will fall onto a few powerful players with specialized customer relations. Finally, the significance of maintained national security and the dominant role U.S. military superiority has in the ultimate balance of global economics suggests the existence of an eventual growth phase for the defense sector, leading to a future period of increased attractiveness in this industry.

The 1990s mark the beginning of a new era for defense contracting in the United States, with streamlined procurement practices and strategic initiatives which demand unprecedented efficiency in the design, manufacture, operation, support, maintenance, and disposal of complex systems. Dual-use technologies, information systems technology, flexible and automated manufacturing, and agile business practices are setting the technology development direction for the U.S. industrial base as the end of the 20th century approaches.

Customer needs are evolving toward knowledge-based systems, where high bandwidth information transfer technology is linked with wide area surveillance and high resolution imagery. A focus for military technology is to eliminate any possibility of friendly fire in times of battle by knowing in real-time where the opposition forces reside and how to most effectively use precision system guided weapon technologies to capture a strategic battlefield advantage. Future technology development should focus on achieving optimized resource allocation and a one target one weapon capability. Refer to Exhibit 2.1.1.3-1 for an illustrative summary of the Five Force Analysis.

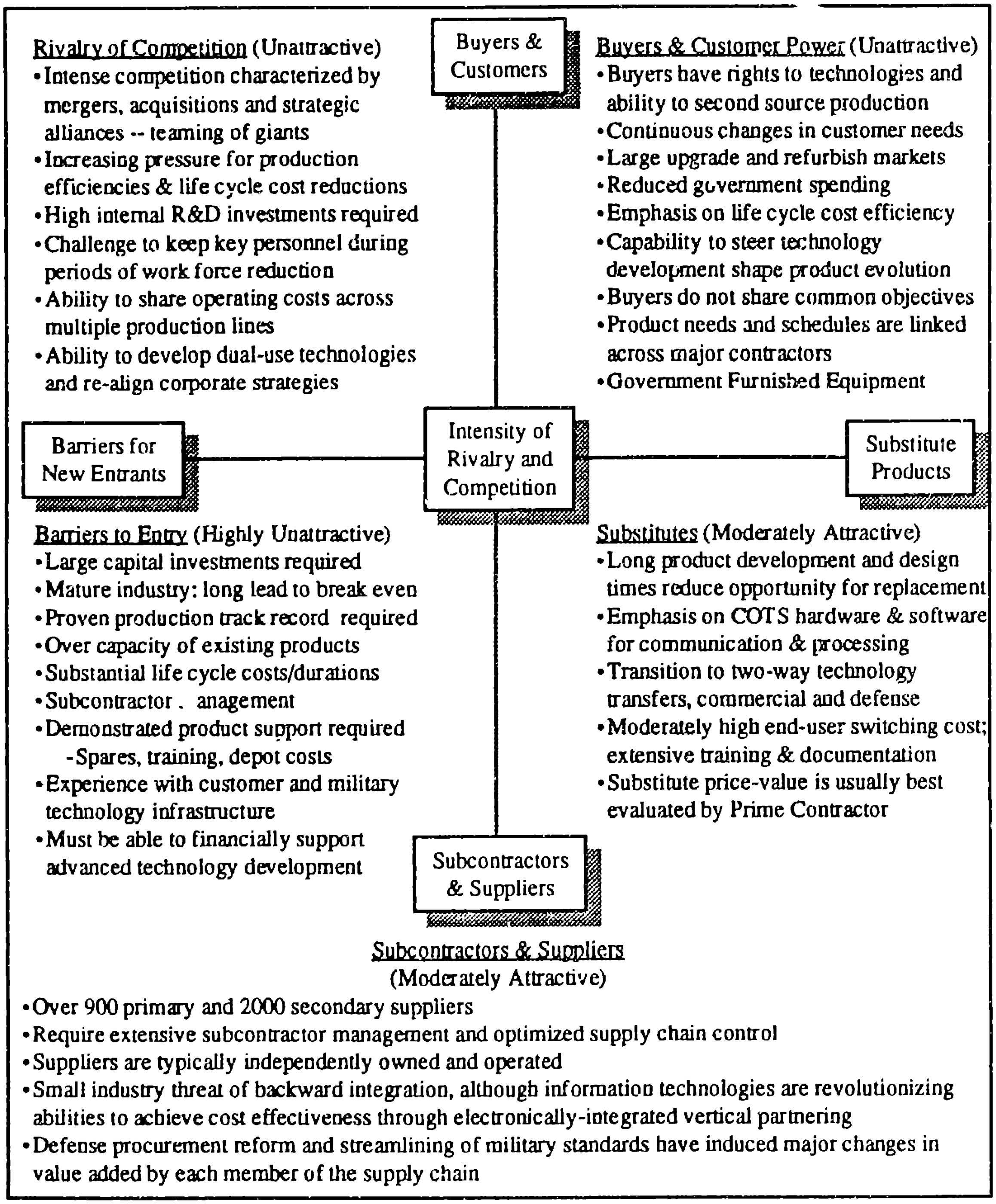


Figure 2.1.1.3-1: Porter Five Forces Analysis for Defense Prime Contracting in the 1990s [3]

Source: Adapted from Ayoob, *Aerospace Defense Contracting in the 1990s*, August 1995

2.1.2 The Commercial Sector

Analysis of the defense industry provides one perspective in determining a direction of competitive advantage in aerospace and electronics. The commercial sector represents another substantial piece of the story. Examples of commercial applications for aerospace and electronics technologies include a wide variety of products, from satellite telecommunications and air transport systems to spacecraft design and consumer electronics. A general divergence between traditional market force analysis in the defense and commercial sectors resides in the fact that traditional technology demands in the commercial sector have lagged the performance capability demands required by many military products. With the explosive growth of consumer electronics such as the revolutionary advances in desktop computer processing power, the present generation of high-tech systems continues to witness a closing of the gap between the technical demands of the two sectors.

As established in the previous section, changes in technology demand from the defense sector are resulting in a major movement toward developing innovative dual-use technologies and increasing opportunities for incorporation of commercial-off-the-shelf components in future military systems. This section addresses the market force analysis in the commercial sector from two perspectives, with an intention to describe the present U.S. situation in terms of several objectives required to remain competitive on a national level. The first discussion presents the United States aggregate market position in electronics production, emphasizing electronics packaging and manufacturing and using optoelectronics as one direction for future growth. The focus on general producibility issues and optical systems ties directly back to the proposed multi-product adoption strategy of investing in dual-use information technologies and advanced sensor systems. A second perspective is presented which takes a more microscopic level view into modern trends in system engineering and management in the aerospace and electronics industries. The second discussion presents recent developments at Boeing in business process reengineering, introducing a system design and management concept which has been highly successful in reducing the non-value added time from Boeing's product development process for commercial air transport.

In this section, the selected examples from process-oriented system engineering, product development, lean manufacturing, and technology insertion are intended to provide sufficient background in commercial aerospace and electronics to establish merit for the multi-product adoption model strategy presented in Chapter 3.

2.1.2.1 U.S. Competitive Position in Electronics/Optoelectronics Technology/Production

As the world enters a period of unprecedented growth in global high-technology markets, the United States has fallen behind Japan in almost every electronics production technology [38,39]. Japan has achieved distinct advantage in electronics production and process technologies through a strategy to develop low-cost high-volume consumer products. U.S. electronics manufacturers have lost market share to foreign-owned or foreign-based manufacturers while U.S. Government funded research and development has dwarfed that of foreign governments.

The Japanese Technology Evaluation Center (JTEC) is a collaborative effort to created to assess the position of the United States relative to Japan in certain key technology areas. The competitive analysis presented in this section stems from several investigations of Japanese and U.S. technologies and capabilities by JTEC panel experts in conjunction with four U.S. Government agencies: the Advanced Research Projects Agency (ARPA) of the Department of Defense, the Department of Commerce, the National Aeronautics and Space Administration (NASA), and the National Science Foundation (NSF). A brief synopsis of the findings of the JTEC panel studies is useful to develop motivating forces behind the multi-product adoption model strategy.

Exhibit 2.1.2.1-1 presents a summary of principal conclusions of the JTEC panel on electronics packaging and manufacturing. These conclusions suggest that the United States must not only fight to accelerate cost-efficient production capabilities, but also must take appropriate measures to re-secure a leadership position in developing innovative enabling technologies in selected critical areas. Optoelectronics is considered a critical technology for future defense-related products, and is also a key technology area for dual-use application. Products which use optoelectronic components include data storage devices and infrared imaging arrays. Exhibit 2.2.1.1-2 presents a synopsis of conclusions drawn from an evaluation of United States competitive position relative to Japan in optoelectronics. The significance of these findings resides in U.S. capability to maintain national defense superiority and remain a world-class competitor in developing electronics technologies.

Electronic Packaging and Manufacturing in Japan [37]

Principal JTEC Panel Conclusions

1. Japan leads the United States in almost every electronics packaging technology.

2. Japan clearly has achieved a strategic advantage in electronics production and process technologies.
   - Because process technology improvements allow for quality improvements and cost reductions in end products, Japan's continuous perfection of its electronics manufacturing systems has enabled it to take market leadership away from technology innovators in the United States.
   - It is apparent that due to successes in process improvement, Japan will be a primary world supplier not only of electronics products and components, but of electronics manufacturing equipment.

3. Japan has established this marked competitive advantage in electronics as a consequence of developing low-cost, high volume consumer products.
   - Japan's success is not a consequence of major technological breakthroughs, but rather a process of continuous and incremental improvements in the technologies of mass production—driven by products such as camcorders and cellular telephones, for which the emphasis has been on miniaturization, low cost, lighter weight, and portability. Those same features are now apparent in notebook and subnotebook computers and in personal and wearable digital assistants, which further demonstrate Japan's product "portability" strategy.

4. Japan's infrastructure, and the remarkable cohesiveness of vision and purpose in government and industry, are key factors in the success of Japan's electronics industry.

5. Although Japan will continue to dominate consumer electronics in the foreseeable future, opportunities exist for the United States and other industrial countries to capture an increasingly large share of the market.
   - The United States in particular controls much of the technology that will drive the future consumer electronics: telecommunications, computers, microprocessors, and software.

6. The JTEC panel identified no insurmountable barriers that would prevent the United States from regaining a significant share of the consumer electronics market; in fact, there was ample evidence that the United States needs to aggressively pursue high-volume, low-cost electronic assembly, because it is a critical path leading to high-performance electronic systems.
   - The United States has the technological edge, ... Japan has the edge in production technology. The country that excels in both new technology and production technology will lead the world in consumer electronics.
   - Advanced technology continues to be the heritage of the United States; if a similar focus can be placed on production technology, the United States can capture a dominant share of the consumer market. Continuous corporate reengineering, an emphasis on concurrent development, partnering between suppliers and customers, and further commitment to enhancing the skills of the workforce are critical success factors that must be addressed.

Exhibit 2.1.2.1-1: Principal Conclusions from JTEC Panel Study on Electronics Manufacturing

Source: *JTEC Panel Report on Electronic Packaging and Manufacturing in Japan*, February 1995

Relative Status of U.S. and Japanese Optoelectronics Technologies [39]

Five topical areas that are believed to be most economically strategic to both Japan and the United States:

1. Optoelectronic systems; emphasis on telecommunications, networks, and optical interconnections
2. Optical storage technology
3. Waveguide devices and optoelectronic packaging technology
4. Photonic devices and materials, with emphasis on laser and optoelectronic integrated circuits
5. Optical sensor technology

The overall assessment is that Japan clearly leads the United States in consumer optoelectronics, both countries are competitive in the areas of communications and networks, and the United States holds a clear lead in custom optoelectronics.

- The largest area of new opportunity for growth in the U.S. optoelectronics industry appears to be optical sensor technology. Japanese R&D posture in this field lags behind the United States and is expected to remain behind for some time. It also appears that the sensors field has tremendous growth potential that U.S. industry is well-positioned to exploit.

- One other area where the United States might succeed in capturing a significant market share is optical storage. At present, Japanese photonics industry is ahead in both manufacturing and R&D for optical storage, but several opportunities exist for major advances in read/write devices and in storage media technology. Thus, the United States has several realistic opportunities to gain market success on the basis of rapidly evolving technologies.

Japan now dominates some 90 percent of the world's optoelectronics markets and can be expected to continue its dominance for a number of years. The current size of the Japanese optoelectronics industry is $40 billion; that of the United States is $6 billion. Obviously, Japan has had enormous success with its development strategies for optoelectronics.

Japanese technological and business success in the field of optoelectronics has been based primarily on telecommunications and consumer products. In particular, the strong, long term commitment to large-scale, low-cost manufacturing has provided Japan with the means to dominate the fields of optoelectronic displays, fiber-optic gyros, and compact disk players. Announcements by Pioneer, TDK, and Idemitsu that they will be introducing the first organic light-emitting flat panel displays in early 1996 also indicate the ability of the Japanese R&D establishment to retain innovative edge in high-volume, consumer-based products targeted by U.S. industry as having fundamental strategic and economic importance.

Exhibit 2.1.2.1-1: Principal Conclusions from JTEC Panel Study on Electronics Manufacturing

Source: *JTEC Panel Report on Optoelectronics in Japan and the United States*, 1996

Japanese strength in the industries such as electronics (and automobiles) appears, at least partially, to be due to a major cultural difference from the United States. Japanese industry relentlessly pursues continuous improvement in both products and processes, developing high-volume international markets to fuel their high technology projects. "Once a need is identified and a technology is brought to a suitable stage of development, Japanese companies invest the resources and infrastructure needed to bring cost and capacity within their projected requirements. This level of forward planning appears to be well developed in the Japanese photonics industry and largely absent in the United States [37,38,39]."

If U.S. high-tech industries intend to remain a world-class advanced technology leaders, drastic cultural change is required on at least two dimensions.

(1) Electronics manufacturing and packaging systems must be designed which are lean and efficient, and which provide sufficient mechanisms for quality control with minimal rework.

(2) Core technology development must be treated as separate from integrated product design with managers who recognize the different missions and needs of the teams who execute each process.

As the boundary which segments commercial and defense components manufacturing begins to fade, the U.S. industrial base must recognize that the next generation of world-class technologists will not solely be the innovators and "dreamers" of what could be, but rather will be those who collectively find an optimal balance of commonality and standardization with flexibility and specialization. Multi-product adoption is one school of thought on how to stimulate and manage the process of this inevitable required change.

2.1.2.2 Designing the Design Process—Boeing's Approach to Process Reengineering

In December 1995, Dr. David L Grose from Boeing visited MIT to describe a system-oriented approach to aerospace product development that provides a more comprehensive assessment of both advanced technologies and feature parameters that characterize a new design. It has been suggested that future product competitiveness will require fast response to customer needs, minimum life cycle cost, and high production quality. For commercial transports, these demands translate into minimum product development cycle time, low cost of ownership, high dispatch reliability, low maintenance, and the elimination of manufacturing rework. While functional organization of the design process has served well in the traditional performance requirements dominated project environment, it is likely flawed when applied to projects which are more time/cost-dominated. To address this challenge, the Boeing Commercial Airplane Company has been investigating the potential of restructuring the aircraft design process based on information flow as opposed to functional organization of the design process.

Boeing has developed a new process prototyping concept called Cross-Functional Integrated Design (CFID) which can be used to assist managers of complex engineering projects to design the design process. CFID objectives at Boeing include:

- reduce design cycle time by 50% over 3-5 years
- accomplish process re-engineering to a data-driven process rather than the traditional functionally driven design process
- focus on practical issues of implementation and execution
- improve management of the exchange of information across functions and tools
- capture 50% of all non-value-added time in the product development process (note: the estimated non-value added time represents approximately 80% of the total effort time, locked primarily in the collection of data, interfaces between functional groups, etc.)

In order to identify areas for improvement and to facilitate the process of implementing the organizational and cultural changes required to achieve the CFID objectives, a software tool has been created by Boeing called Integrated Computer-Aided Design (ICAD). ICAD facilitates the CFID effort through knowledge-based tools to incorporate concepts of design, manufacturing, and finance systematically at the engineering design level. Engineers work in an integrated product team environment where multiple disciplines are represented simultaneously. Refer to Figure 2.1.2.2-1 for a top-level motivation for the CFID process reengineering objectives at Boeing.

Current Approach (Functionally Organized)	Problems with the Functional Approach	Consequences of the Functional Approach
• functional relationships, historical basis, traditional heritage driven vertical integration • task oriented: individual understanding of entire system is lacking • airplane performance dominates the design process, inappropriate for design-for-cost projects • manufacturing is addressed only in downstream detailed designs	• technical design, manufacturing and marketing support are isolated instead of integrated • introduction of new technologies needs to be refocused for recent shift in objectives (i.e. cost) • if design specifications (SFC, weight, payload, range, etc.) are not met then Boeing pays the price for the entire life cycle of the vehicle	• design cycle time is too long • design process is schedule driven • early performance focus does not uncover the cost risks • fragmentation of responsibility • legacy software, tools and methods focus on single perspective, lacking "system" view

Figure 2.1.2.2-1: Motivating Factors Behind Boeing's CFID Approach to Process Reengineering

A system design process defined by "flow of data" as opposed to "flow of tasks" can be accomplished using centralized computer-based methods. In developing these universal changes to system engineering practices and product development tools, several general communication issues must be considered. In order to implement a data-driven integrated process, vocabulary across functional disciplines is required. The backbone interface for connecting and integrating all the individual engineering tools used by the different functional groups must correctly "translate" to the common vocabulary to ensure full compatibility and tractability. Using this approach, a shared database can be constructed to facilitate engineering design and minimize change orders and rework.

In order to reduce development costs and accelerate product development, the engineering design process must be reengineered to be more overlapping in nature. For extremely complex projects such as the design of commercial air transport vehicles, this introduces a notion of "concurrent engineering in the large [26,99]." To date, the data flow process has shown very promising results at Boeing, yielding a 40 percent reduction in design cycle time over previous generations based on historical data.

There has been considerable resources invested in developing scalable technologies for applying fundamental concurrent engineering concepts to very complex highly integrated projects. The results have introduced the birth of the integrated product team paradigm. Much of this theoretical research will become more common in practice as computer information systems become more aligned with the operational needs of technology-based companies.

In Boeing's commercial air transport business, making decisions on production go-ahead with incomplete or inconsistent data currently results in approximately 40% rework after initial design is complete. The current functional approach forces engineers to pass on incomplete work to next functional task if a project milestone must be met and the work is behind schedule. The CFID process manages the data better by passing on work implicitly with indicator of degree complete using color-coded on-line simulation which is accessible by every engineer and manager on the project. Everyone involved in the project, whether collocated or not, can log into central database and view the progress and status of the entire project. Individual task items are color coded in an integrated master plan and schedule. The colors indicates a level of completeness for every task. Therefore, mechanical design engineers are able to post preliminary analysis and tradeoffs, and update the status of these items as the system evolves. Downstream tasks with precedent relationships, such as avionics and flight control system design, can proceed with greater ability to overlap predecessor tasks. This system has been shown to be an effective means to optimizing management decisions, ultimately leading to an ability to accelerated product development requiring less rework.

The conclusions from the Boeing system engineering case study are straightforward. In the most pessimistic case, even if using the CFID process results in similar development cycle time, significant reduction in required rework is expected, which yields reductions in time and money needed to complete the project. The real value of methodologies such as the data-flow process computer implementation of CFID can only be established and measured if mapped into a context of shareholder value in terms of finance and manufacture advantages. The message behind these efforts is one of reduced costs and higher profitability or pricing advantages to the company. Design-for-cost using CFID can provide insight into optimal allocation of resources in systems, finance, and structures and manufacturing. In reengineering the design process, there must be an attempt to upgrade the corporate policy to a new organizational model, one which is flat, flexible, networked, diverse, and global.

Re-organization presents a new challenge to the engineering community, a tradeoff between power and influence. In the traditional model, individuals gain power with experience; in the new model power is replaced by influence due to design team unified actions to achieve common goals. Practical considerations to accommodate the existing infrastructure of management and mitigate the risk of completely replacing proven legacy software suggest an incremental transition to a new system which supports multidimensional optimization is required. CFID "embeds" existing legacy programs, rather than attempting to completely replace a functional structure, to allow a slow paced low-risk transition to the new model. Ultimately, the intention of CFID is to have the corporation migrate to the process-oriented new organizational model on a macro level.

Several conclusions can be drawn from the CFID initiative at Boeing:

- Improving competitiveness cannot rely on technology advancement alone.
- A system-oriented data-driven approach offers cost and development time advantages over conventional functional-driven approaches for commercial aircraft design.
- Focus should be placed on reengineering the design process around the flow of information.

CHAPTER 3. MULTI-PRODUCT TECHNOLOGY ADOPTION

3. STRATEGIC TECHNOLOGY DEVFLOPMENT THROUGH MULTI-PRODUCT ADOPTION

Multi-product technology adoption is an engineering-based strategic approach to leverage modern technical advancements and emerging information system infrastructure resources to respond competitively to the evolutionary changes in the global economy. Using this model to capture an understanding of the present and future state of today's technology-based industries, a direction for optimizing future growth and profitability can be identified. This model builds from fundamental guiding principles for strategic management and system design to establish key indicators for successful technology development through cost-effective multiple product insertion.

3.1 The Multi-Product Adoption Model

3.1.1 Three Tiers—Strategy, Structure, and Implementation

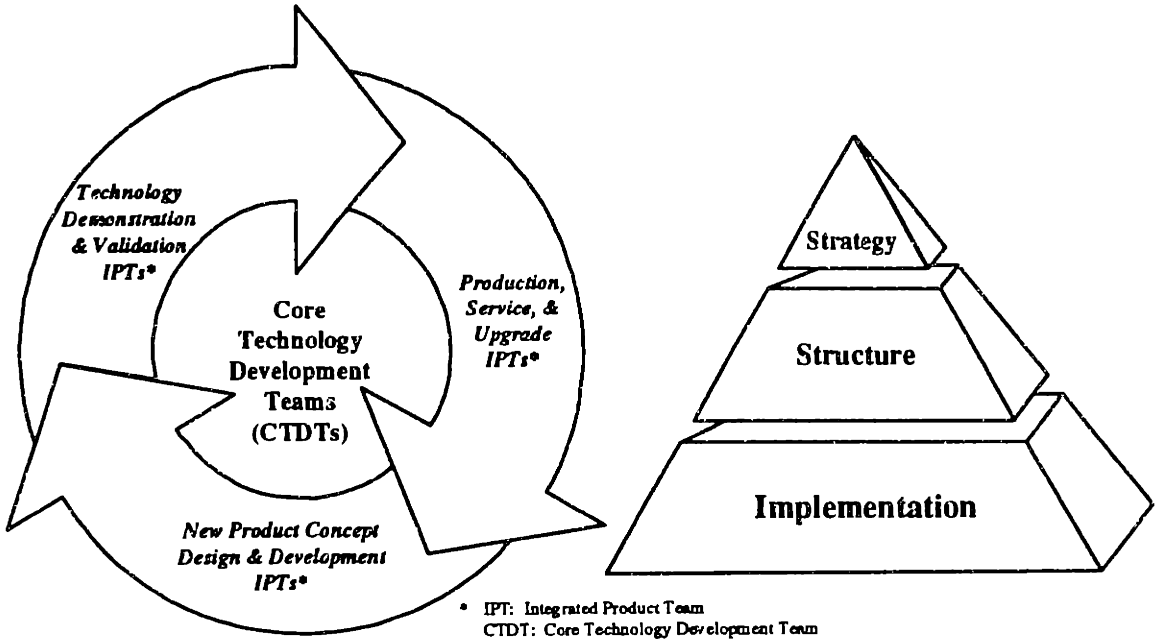
Strategy

The main objectives of the multi-product adoption model are to provide an analytical framework for understanding dual-use technology development, and to establish a set of flexible structured guidelines for implementing and managing the multi-product adoption process. In principle, the success or failure of technology ventures may be determined by two related factors, assuming that the commitment to developing the technology has been made:

(1) technical feasibility given current theoretical and practical constraints;

(2) resource sufficiency and allocation—staffing, capital, equipment, etc.

Technical feasibility is most appropriately treated on an individual case-by-case basis. But resource sufficiency and more specifically, strategic allocation and management of resources, can be handled more generally in an optimization context. The multi-product adoption model strategy optimizes technology development efforts in terms of cost-efficiency and payback period. System engineering and strategic management theory suggest existence of an optimal configuration of resources which most effectively handles the parameters governing the process of cost-efficient enabling technology development. The multi-product adoption model addresses this strategic resource allocation problem by directing operational actions to achieve short-term tactical objectives while maintaining a consistent commitment to corporate longevity and future growth. Figure 3.1.1-1 illustrates some of the main themes of the multi-product adoption model.



Strategy

- Focus on Selective Dual-Use Technology Development for Defense & Commercial Markets
- Recognize All Opportunities for Technology Insertion, Capture Most Promising Candidates through Assessment Based on Core Competencies and Existing Customer Types
- Maintain a deliberate distinction between the roles and missions of IPTs and CTDTs
- IPT mission: deliver quality, reliable, cost-efficient products which house core technologies
- CTDT mission: develop highly modular, easily tailorable technologies to multiple IPTs
- Leverage the Information Revolution to Facilitate Vertical Partnering
- Develop a Philosophy of 360-Degree Product-Technology Integration

Structure

- Maintain/Establish "Permeable Boundaries" with Flexible Interface Between CTDTs & IPTs*
- Balance New Development Efforts with Existing Product Upgrades
- Align Technology/Product Development with Interpreted Technical Needs and Customer "Types"
- Incorporate Joint Product-Technology Working Groups wih IPDT and ITDT Representatives

Implementation

- Multi-Product Adoption Tool Set for Adcanced System Design and Management
- Modernized Information System Infrastructure and Computer Networks
- Core R&D Led By CTDTs with Rotating IPDT Members Encourages High Level of Interaction
- Vertical Integration of Key Subcontractors & Suppliers Using Modern Information System Technologies
- Participation in Selective Government-Industry-University Partnerships

Figure 3.1.1-1: Multi-Product Adoption Model—Strategy, Structure, and Implementation

As indicated in Chapters 1 and 2, current market forces in the aerospace and electronics industries demand high quality technical performance and simultaneous substantial reductions in product life cycle costs. In response to this demand, research in industry and academics has focused on establishing "best practices" for product development. One key result of this research has been the widely adopted integrated product and process design team concept. In the struggle to achieve high cost efficiencies through integrated product design teams (IPTs), high-technology industry in the United States should not fail to recognize the process elements of an existing system which has produced generations of Nobel Prize winners in the scientific community.

Structure

A basic tenet of the multi-product adoption model is to preserve the innermost core technology development from being completely absorbed into product-dedicated IPT structures. This approach is not intended to isolate IPTs from the technology development process, but rather to have IPTs act as "customers" to core technology development teams (CTDTs) in a fully networked hub-and-spoke organizational structure. See Figure 3.1.1-2.

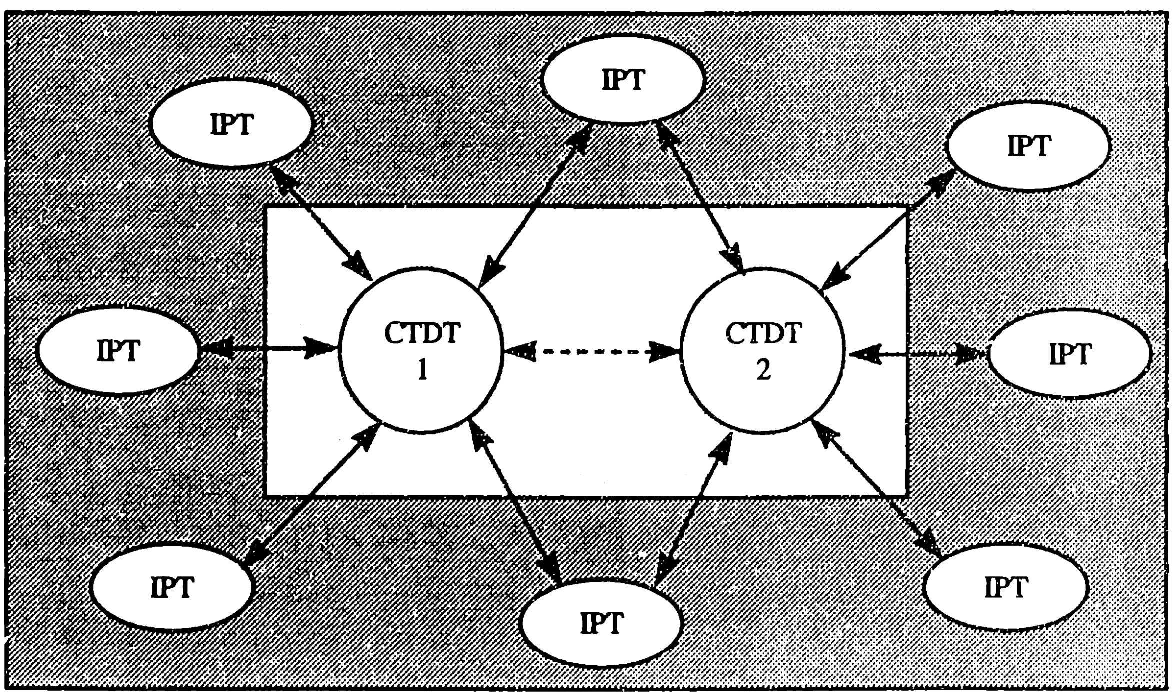


Figure 3.1.1-2: Multi-Product Adoption Model Networked Hub-and-Spoke Organization

This networked hub-and-spoke organizational concept serves as a set of flexible guidelines for the implementation which supports the structure concept of maintaining "permeable boundaries" between IPTs and CTDTs. As illustrated in Figure 3.1.1-2, some IPTs incorporate more than one core enabling technology. The interfaces between the IPTs and CTDTs, shown as two-directional arrows, are explicitly intended not only to indicate the transfer of producible technologies to products, but also to illustrate a structured process of rotating IPT members periodically into CTDT processes in order to ensure maintained alignment of core technologies with existing customer values. The rotating membership scheme encourages a high level of interaction among core technology development efforts and integrated product design. In doing so, direction is given to CTDTs in terms of developing dual-use technologies for multiple product insertion, and IPT members are exposed to future technological capabilities allowing the solicitation of informal customer feedback in an attempt to identify latent customer needs for revolutionary new products.

The multi-product adoption model rotating team member approach assumes that customer needs and values are sufficiently understood by all IPT members, an assumption which is completely valid if one considers a fundamental element of the IPT concept is to incorporate the voice of the customer into the product development process using a tool such as Quality Function Deployment, or QFD [12]. This entire discussion assumes that the reader is familiar with the widely recognized concept of IPTs, and specifically that there is a major difference between IPTs and multi-discipline engineering teams. A product team only becomes an IPT by including representatives from marketing, manufacturing, integrated logistics, engineering specialties, and if at all possible, the customer. IPTs promote an environment which fosters team learning through all members of the team becoming intimately familiar with the issues of all major aspects of the system design. Routine informal meetings integrate the design process to inform all team members about overall program status as well as individual subsystem designs. Rigid functional boundaries to responsibility segmented along system interfaces are highly discouraged. This team-based approach is a radical departure from "old school" system engineering design methods.

The multi-product adoption approach encourages IPTs to incorporate producible technologies developed by CTDTs with as minimal "tailoring" as required in order to facilitate flexible manufacturing through product modularity, platform-based design, and multi-industry vertical integration. A significant distinction is made here between what is meant by "product modularity" and the product development concepts of "modular versus integral design functionality." Product modularity in this context is intended to mean commonality of key technology components or processes across multiple product lines. A product can simultaneously support integral design functionality and consist of a highly modular physical design architecture. This thesis suggests that it is this balance of technological modularity and functional integration which can be exploited to yield synergistic benefits in reducing life cycle cost and improving producibility and serviceability. The ability to share technology across products is dictated in large part by decisions made by CTDTs. The decisions involving modular versus integral design functionality reside with the IPT development processes and are, as they should be, left as highly dependent on the particular product being designed by the IPT.

It is well recognized that the fundamental strengths of IPTs reside in the interactions of team members from disparate fields to combine areas of expertise to achieve systemic improvements in product design efficiency. In the industrial movement toward organizational structures which support integrated product design practices, the interactions among different IPTs can be explicitly structured and leveraged in order to strengthen core technology development efforts. The concept of CTDTs attempts to maximize the value added by each IPT, and capture additional synergistic effects by rotating IPT members into core technology development efforts led by teams of CTDT specialists. By having representatives from different IPTs participate in technology development, two complementary opportunities are seized—the ability for several IPTs and their associated product and process designs to simultaneously influence the direction of core technology evolution, and the realization of accelerated multiple market insertion for production-ready core technologies.

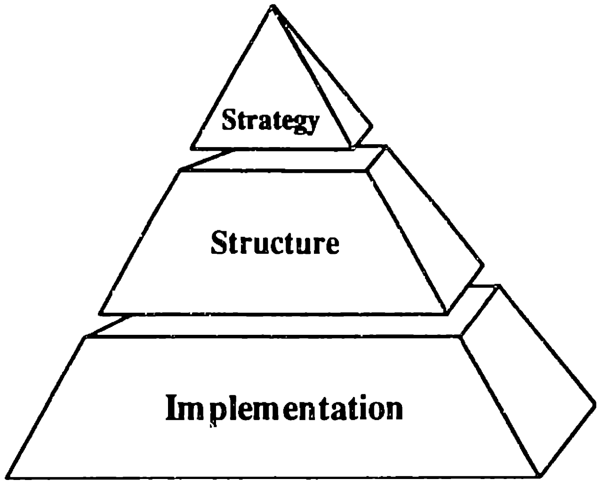
Implementation

Many tools have been introduced by industry and academics to facilitate concurrent engineering and accelerate product development to achieve early market penetration and capture "first player" advantage. A selected set of such system design and management tools serve as one component of the implementation tier of the multi-product adoption model. The multi-product technology adoption model presents one possible approach for enhancing the ability for a high-tech organization to continue to pursue quantum leaps in technology development while simultaneously maximizing affordability of integrated product and process design.

The implementation tier of the multi-product adoption model consists of a tool set for complex system architecting and strategic management of resources. A tremendous amount of literature has published for many of these types of techniques. Discussion of some specific tools suitable for the multi-product adoption model is given in Section 3.1.2. Since the multi-product adoption model has been constructed in response to the evolutionary changes occurring in the aerospace and electronics industries in the United States, it should not be surprising that many of the tools are parallel to those which have proven to hold high value from integrated product design practices for aerospace and electronic systems.

With the challenges of competing in today's global marketplace, supplier management and vertical partnering have become increasingly significant for achieving competitive advantage. Integrated technical information systems play a key role in developing high technology products, especially when engineering design is divided across two or more company sites or multiple subcontractors. By fully utilizing currently available networking capabilities, a secured system can be constructed to achieve efficiencies in subcontractor relations through centralized engineering database access and integrated customer-contractor-supplier information systems. One of the multi-product adoption model tenets is to maintain a modernized information resources system infrastructure, providing the capability to capitalize on the cost savings achievable from using electronic information technology and computer networking resources to manage revolutionary change in key subcontractor vertical partnering. Vertical partnering issues are discussed further in Section 3.1.3.

Participation in government-industry-university partnerships is becoming a key process element in today's technology development business models. Several initiatives have been implemented by the United States Government to stimulate partnerships which gain benefits from establishing a formal link between industry and academic research. Many manufacturing-based companies have reduced the size of in-house research laboratories, focusing investment on immediate problem solving as opposed to long-term basic scientific research. Industry has become the short term "producer" while universities have emerged, or perhaps remained, the long term "research performing" institutions. Investment from industry and the government can fuel the "outsourcing" of research to universities with industry serving as a technology "steering committee" while primarily focusing on production objectives. The long-term benefit of this type arrangement is a coordinated alignment of industry's technological needs with basic academic research and development, leading to the convergence of the demand for a well-educated and highly skilled work force surrounding business centers of excellence with sustainable growth and corporate longevity.



Discussion of Model Concepts

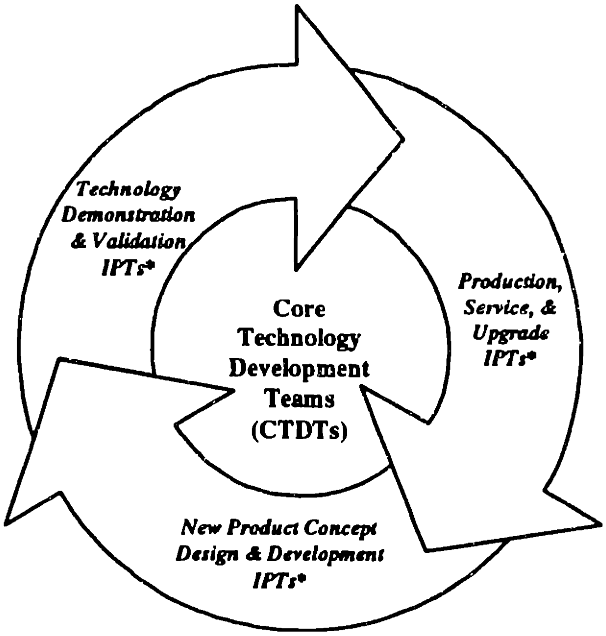
Using a set of general guiding principles for complex systems architecture as a point of departure, the strategic tier of the multi-product adoption model focuses on preserving (and enhancing) the ability of a company to develop core enabling technologies through scientific research. Strategic intentions are linked with structure and implementation. The structure tier provides flexible guidelines for architecting the most effective organizational structure to support the multi-product adoption strategy, and the implementation tier incorporates modern systems engineering and management tools to best achieve the model objectives. In conjunction with the advances in modern information systems technology, the multi-product adoption model leverages the explosive growth of computer processing resources to achieve distinctive advantages toward achieving cost-efficient core technology development. Each tier in the hierarchy is essential in achieving the model objectives.

The three tiers of multi-product adoption are linked together through common short term and long term goals. Strategic objectives of the model are to provide the technological growth demanded by the customer base at an affordable cost, and to attain sustainable competitive advantage through innovative system design and management practices. By focusing on core competencies and selective well-matched dual-use enabling technologies, short term and long term goals can be balanced to achieve efficiencies through cost reductions for development and production shared across multiple products.

In order to fully exploit the advantages of developing dual-use technologies, a comprehensive search of potential product applications must be performed. Attempts must be made to identify latent needs as well as immediate needs of existing customers and emerging markets. After considering commonality among customer types and existing product sales distribution networks, a selection process narrows down the product applications to a linked set. IPTs work with CTDTs to bring the technology to a "tailored" production-ready state appropriate for system integration. For example, the production of high resolution Infrared Focal Plane Array (IR FPA) detectors represents a modern technology candidate for multi-product adoption. IR FPAs produced on the same manufacturing lines can be used in missile seeker systems and commercial infrared imaging cameras. The IR cameras can be marketed in diverse product applications ranging from improved night vision to state-of-the-art thermographic analysis for medical screenings. Several detailed case studies of candidate technologies for multi-product adoption are given in Section 3.2.

A major element in the multi-product adoption model is the intention to account for the value in recognizing common "customer types". In this context, customer type is defined as segmentation and aggregation of an existing customer base along lines of common procurement practices and production lot scope. For example, a company which typically has a major proportion of sales to government agencies, such as a prime contractor for the development and production of defense systems, can expect to achieve a greater probability of success in expansion of products and services to other customer bases which share common procurement practices to the U.S. DoD. When new market penetration includes risk, possibly hidden risk, due strictly to the fact that it is new, one strategy is to partner with an existing player for product introduction. In order to maximize the probability of success with the development and application of dual-use enabling technologies, the multi-product adoption model strategy recognizes the significance of exploiting similarities in customer type and the ability to leverage existing sales distribution networks.

Although this strategy may appear trivially obvious, it is worth noting that many tactical product diversification efforts seem to lose sight of fundamental business principles. As discussed in Appendix 2, Raytheon's strategy to become a high technology commercial corporation while remaining a top-tier competitor in defense has been very successful in evolving core competencies in the development and quality production of radar systems and other military technologies from defense applications to new commercial markets. Examples include wide area surveillance, air traffic control, transportation systems, weather monitoring, and wireless communications. Most successful large scale product diversification efforts for Raytheon have been focused on "government-like" customers. In making the transition from a defense contractor to a multi-industry commercial company with strong defense operations, Raytheon has had to be very selective in the process of transferring defense technologies to commercial applications. Coupled with foreign sales of military technologies, these ventures have collectively launched Raytheon into a position as a leading global competitor in many of these areas.



A concept of 360-degree integrated product-technology development balancing new product development with tactical upgrade production is one of the main philosophies central to the multi-product technology adoption model. This philosophy suggests that technology development should be a directed semi-independent process from integrated product design, with performance criteria which include feasibility, cost, quality, future growth/payoff probabilities, producibility, systemic issues, licensing, etc. It is indicative of the existence of an optimal point in strategic resource allocation, where there is a balance between new product concept development, system demonstration and validation, and service/upgrade programs. This strategy is somewhat similar to hedging practices for mitigating risks in financial markets, or finite horizon multidimensional nonlinear optimization problems in optimal control/estimation theory.

Since life cycle affordability and cost of ownership are driving elements in determining the success of complex products, the multi-product adoption model incorporates mechanisms for balancing technical performance metrics with producibility cost metrics. Cost is treated as an independent variable, and engineering decisions made early in the concept design include producibility issues and pro-active measures for reducing life cycle costs. IPTs are encouraged to design products suitable for future upgrade, especially for products which house multiple technologies with different expected growth and maturity rates.

It is important to realize that the design decisions made throughout the initial stages of a product's life cycle have a substantial effect on the performance-cost tradeoffs made further downstream. Figure 3.1.1-3 illustrates the life cycle development process for a typical aerospace/electronics product or system. The cumulative design-for-affordability payoff is achieved over the life of the product and can be maximized by making well informed design decisions early in the development process. The figure illustrates a generic scenario in which producibility issues are stressed in the early phases of product design—during concept development and demonstration, and engineering and manufacturing development (E&MD).

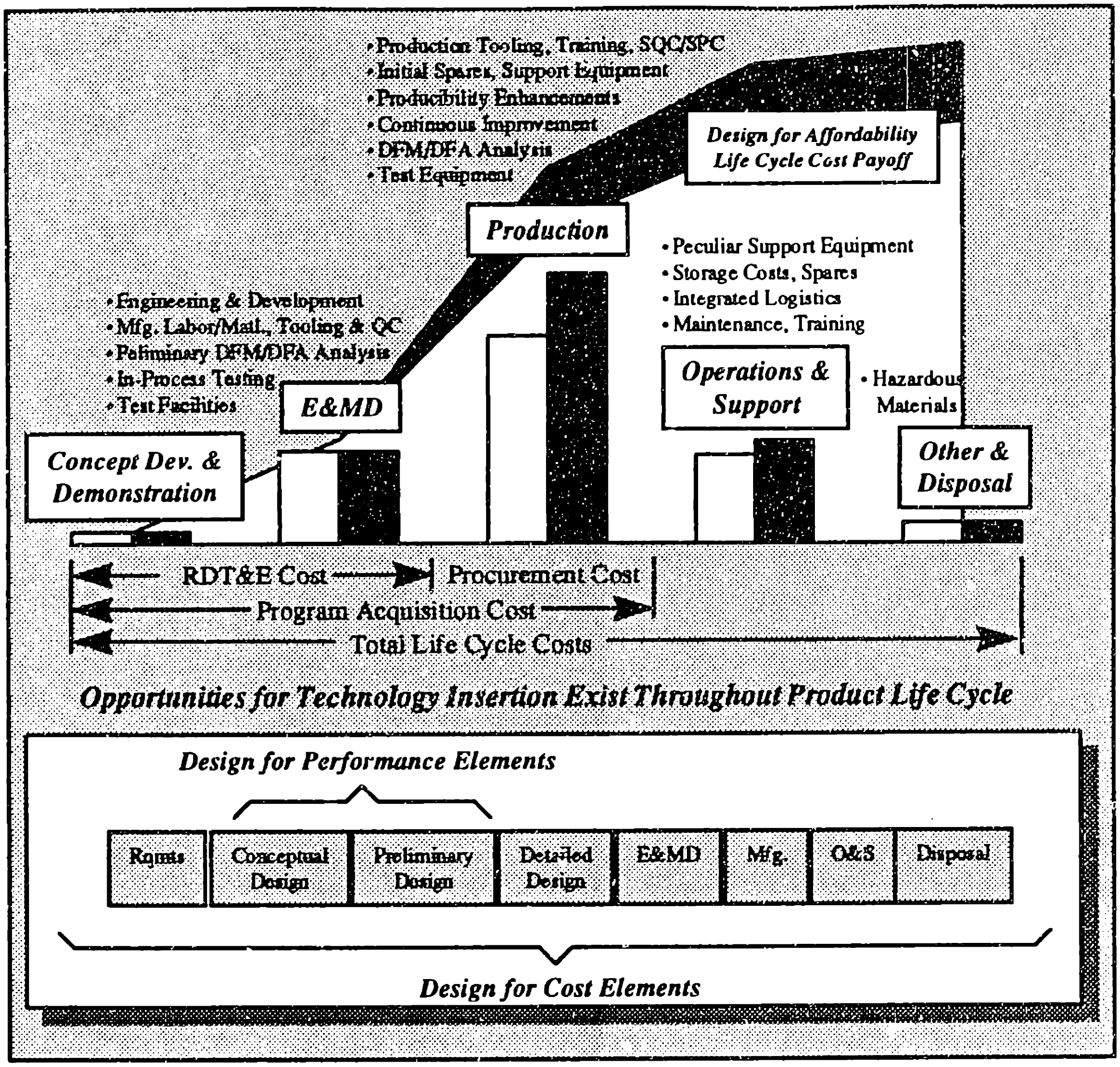


Figure 3.1.1-3: Substantial Life Cycle Cost Payoff is Achieved Early in the Design Process

Pause for Reflection

In the aerospace and electronics industries, there is a tremendous need for accelerated development of advanced systems. With government procurement practices under significant reform to reduce costs, opportunities exist in the aerospace and electronics industries to position strategically for maximum growth potential, profitability, and sustainability. The structure tier of the multi-product adoption model is developed to align technology and product development efforts with the voice of the customer. Joint product-technology working groups and continuous improvement of products, processes, and employee training are a means of maintaining a high-skilled labor force during this period of evolutionary economic change.

In this multi-product adoption model, the unique environment in which pure scientific research and development has historically flourished in the United States is preserved. Because it is recognized that some level of technology growth and evolution naturally resides within product-dedicated design teams, the model structure is flexible. However, it is the intention of the multi-product adoption model that core enabling technologies are developed which can be shared across multiple product applications. The significant issue from research in this area is that because the rate at which individual technologies evolve is different, products which house multiple technologies with different growth rates can be specifically designed with hooks for future upgrade. For example, because the life cycle for a microprocessor is only about 36 months while other peripheral equipment may last several years beyond, the personal computer industry has used highly modular designs to accommodate for future upgrade of individual components. Monitors, printers, modems, disk drives, etc., can all be updated separately if desired.

A more specialized system, such as a dedicated missile digital computer architecture, can be designed to be highly modular and adaptable to many target host products (e.g., other missiles). These architectures can be designed with flexibility for interrupt prioritization and sequencing such that they are easily "tailorable" to multiple operational environments. In addition to the benefits of facilitating re-use of software and increased compatibility, commonality of core components can be used to gain cost efficiencies through economies of scale. Furthermore, since commonality leads to increases lot size demands, vertical partnering and strategic long-term negotiated contracts with provisions for generational upgrades on short life cycle components are attractive to subcontractors as well as primes. As a result, suppliers get more accurate, longer-horizon demand forecasts, and prime contractors acquire greater leverage in negotiating price through larger production orders.

Multi-product adoption embraces the concept of integrated product and process design teams for achieving design efficiencies in cost and function for production-ready technologies. A strategic balance is sought in balancing future research projects with current technology insertion into new products and upgrading existing products. Both the multi-product adoption model objectives and the underlying need to develop dual-use technologies must influence corporate strategy in the United States, with tactical operations and organizational structures re-matched to the evolving needs of today's changing global marketplace.

3.1.2 The Multi-Product Adoption Toolbox

Many tools have been introduced to the modem system design and management community which are valuable to implementing the changes to the multi-product adoption model. Literature on these tools is widespread and the particular combination which best meets the user needs depends on the specific products and/or technologies being developed. Figure 3.1.2 indicates some of the suggested methodologies for implementing the multi-product adoption model. One common aspect of the implementation tier of multi-product adoption is the need to maintain a modernized information system with high bandwidth computer networking capability in order to facilitate vertical partnering and strategic supply chain management using multi-objective optimization. In determining the optimal configuration of product development, design, production, and upgrade projects that a company undertakes, the integration of systems engineering tools for planning and managing large projects can not be understated. Material requirements planning, manufacturing system line balancing, inventory planning, and optimal lot sizes are all facilitated by accurate market forecasts and integration of key suppliers. In the long run, it is economically beneficial to share demand forecast information with suppliers and electronically link subcontractors to prime contractor resources including computer-aided tools. Costs for establishing such a system must be tracked in order to manage an equitable sharing of costs and benefits between contractor and supplier.

Figure 3.1.2-1: A Sample Multi-Product Adoption Implementation Tool Set

- Integrated Master Plan & Integrated Master Schedule (IMP/IMS)
- Design for Affordability; Design for Manufacturing/Assembly (DFM/DFA)
- Computer-Aided Design/Manufacturing/Engineering (CAD/CAM/CAE)
- Supply Chain Management, Lot Sizing Optimization, Economic Order Quantity
- Material Requirements Planning (MRP), Theory of Constraints, Just-in-Time (JIT) Practices
- Integrated Technical Information Services
- Taguchi Methods, Total Quality Management, and Design of Experiments
- Parametric Cost Estimation & Activity-Based Costing
- Design for Six Sigma Quality
- Statistical Process Control & Statistical Quality Control (SPC/SQC)
- Quality Function Deployment (QFD) and the House of Quality (HoQ)
- Competitive Benchmarking
- Pareto Analysis, Pugh Charts, and Structured Concept Selection Matrices
- Focus Groups; the Voice of the Customer
- Team Dynamics and Organizational Processes Analysis

3.1.3 Impact of the Information Revolution

3.1.3.1 A New Way of Doing Business

With the growing capacity for virtual teaming through the expansion of the telecommunications infrastructure in the world, there is great opportunity to exploit information technology for reducing development costs for new products and technologies. Video-teleconferencing, wireless communications, electronic mail, computer networking, standardization of file transfer protocols, and the resources of the world wide web have provided a revolution in the mechanisms available for performing many conventional business operations with increasing levels of cost efficiency. In addition to the potential new avenue for marketing and advertising existing businesses, there is tremendous opportunity for growth in many markets connected to the information revolution—the on-line services industries, computer network hardware, software programming, and system support to name just a few.

This section is intended to motivate further future investigation of the opportunities that the information revolution provides to enhance a company's ability to develop dual-use enabling technologies. Integrated product/process design teams are becoming commonplace in today's business practices, but the relative disadvantages of non-collocation are diminishing due to the emerging capabilities of the information-based infrastructure in the United States and the evolutionary growth of "virtual collocation" through integrated information technical services.

Two specific initiatives are presented in this section:

1. Vertical partnering through integrated technical information systems;
2. Government-industry-university partnerships.

The significance of these two initiatives is that scalable advantage can be captured by leveraging emerging resources from the emerging global information infrastructure. Revolutionary changes in supply chain management include sharing computer-aided resources and the innovation of a near-paperless proposal and bidding process. Electronic communication media should be exploited to capture the vast opportunities for efficiency which exist in today's age of streamlining military standards and implementation of processes for continuous improvement.

3.1.3.2 Vertical Partnering through Integrated Technical Information Systems

Vertical partnering by itself is not a very new concept but with the capabilities being introduced by the information age, the advantages of electronically facilitated vertical partnering have become critical to ensuring cost-effective engineering development and manufacturing. Companies rely on strategic alliances along industry/product value chains to achieve competitive advantage, maintain profitability, and capture sustainable growth. Coupled with the mass movement toward developing the information superhighway and computer integrated technical information services, strategic initiatives for reducing subcontractor relations costs have been investigated through feasibility studies and prototype demonstrations. For example, the ManTech (Manufacturing Technology) initiative under the direction of the United States Department of the Air Force has made progress toward identifying the cost savings potential by streamlining subcontractor-related processes through shared computer-aided design/manufacturing/engineering (CAD/CAM/CAE) resources and centralized integrated product design databases. Figure 3.1.3.2-1 illustrates the concept of vertical partner facilitization through electronic information systems

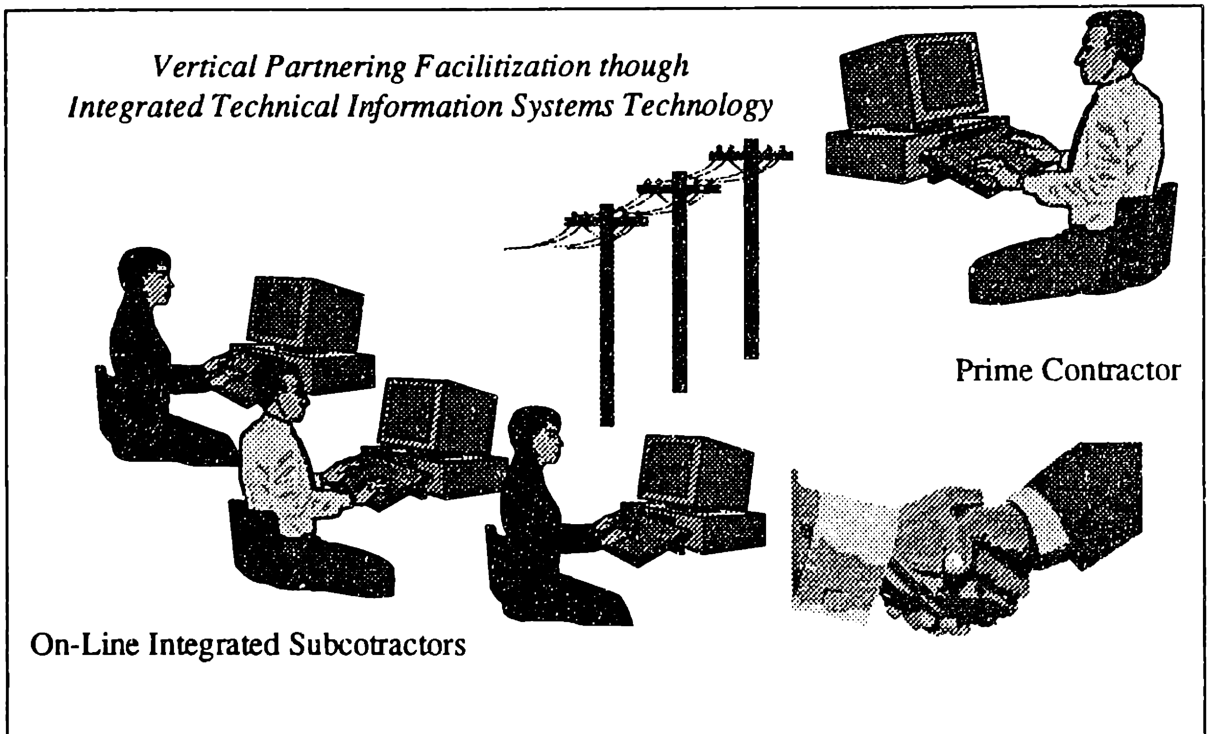


Figure 3.1.3.2-1: Vertical Partnering Facilitization

Many of today's prime contractors for defense technology products serve a value added role in product development in the form of capital investment, computing resources, a few distinctive core technologies, and system integration. In an efficient manufacturing-based economy, much of the unit production cost is accountable through materials and components typically supplied by vendors and/or developed by subcontractors. One major step in reducing development costs for products includes reducing the amount of reengineering required for system integration. In order to simultaneously achieve reduced cost of ownership and accelerated product development, compatibility and producibility issues must be addressed early during concept development and system architecture design and continue throughout the product life cycle. Electronic media and the resources emerging from commercially developed information systems can be leveraged to maximize efficiency in subcontractor alliances. The ManTech initiative is designed to meet these challenges through the innovative utilization of advanced information system technology and through use of the global telecommunications infrastructure.

In order to quantify the extent of savings that the facilitating subcontractor related processes can expect to achieve by utilizing information-based resources such as ManTech, a cost analysis methodology must first be defined. Current processes must be studied and understood, then reduced to distinct actions and events. Unnecessary redundancy can be isolated and removed. Quantifiable cost, performance, and quality metrics must be assigned to the remaining distinct activities to optimize efficiency and to provide a mechanism for evaluating continuous improvement as the optimized process evolves in the future. Using this type of activity-based structure, processes are forced to evolve with the available resources and technologies and should result in maintainable efficient operation. A metric-based efficiency model also results in bounding the achievable benefits of adopting advances in technology which result in early identification of points of diminishing returns to the investing company.

Benefits from the vertical partnering initiatives in the defense contracting manufacturing business are expected to have impact in increasing efficiency in subcontract procedures and operations management. Unique attributes of next generation vertical partnering systems which use the resources of the electronic data transfer and paperless transmission for many of the communication and documentation required to complete tasks in the product development, manufacturing, and assembly process.

Items and concepts for consideration in the transformation to electronic information exchange for achieving greater cost efficiency include:

- 3-dimensional manufacturing drawings;
- electronic engineering change orders;
- the concept of the "paperless" factory;
- documentation for structured and standardized proposal processes;
- automatic routing of design changes or problems to responsible engineer;
- shared CAD resources and integration of change orders into baseline models;
- electronic purchase orders with electronic receipt of notice.

Other significant areas for continuing improvement in manufacturing processes include automated toolpath generation for CNC-machined parts using different software support systems. "Even with the most powerful programming languages, this process is tedious, error prone, and very time consuming. In most cases the probability of error is so high that the subcontractor must cut a sample part to identify errors which must then be re-coded manually [73]." Perhaps the biggest impact resides in an ability for subcontractors to use the prime contractor 3-dimensional solid modeling databases resulting in avoidance of manual reentry of the design or correction of interface program errors between the two sites. A common system would not only maximize compatibility across contractor-subcontractor boundaries but ensure correct communication of specifications. The elaborate programs used by prime contractors generally offer higher levels of automation, they are faster, and are less error prone than lower costing systems used by many subcontractors. Most of the more elaborate packages include error checking and graphical displays to catch machine errors without the need to cut a proof part. The savings to the subcontractor should be significant while offsetting costs to the prime to provide these facilities should be minimal. Later, data could be also be automatically reported to the prime as a significant enhancement to SQC processing.

A Note on Virtual Factories

Research and development for implementing new capabilities in manufacturing electronics and electromechanical devices are leading to realizable software packages which can be used for the design, planning, and partner selection process. "Virtual factories" is a term used to describe an emerging capability to analyze and optimize business decisions before ever entering into contract negotiations. Since multi-enterprise partnerships are a fast growing element of United States industries, resources are being invested to provide software tools which serve as a backbone for integrating existing legacy systems and databases. The motivation for these efforts is to develop a system which can assist program managers and project planners in making decisions involving the concurrent performance of design critiquing, process planning, detailed production planning, and partner selection. Development efforts at the University of Maryland Institute for Systems Research (ISR) have developed a system which will "aid industrial competitiveness by providing ways to rapidly access the cost, performance, and time-to-market of proposed electromechanical designs." The ISR system extends previous work on microwave transmit/receive modules for classification, indexing, and retrieving of process plans. The toolkit incorporates aggregate level evaluation and optimizes over a parameter space including information on each partner's responsiveness, equipment availability, product quality, cost, and lead time.

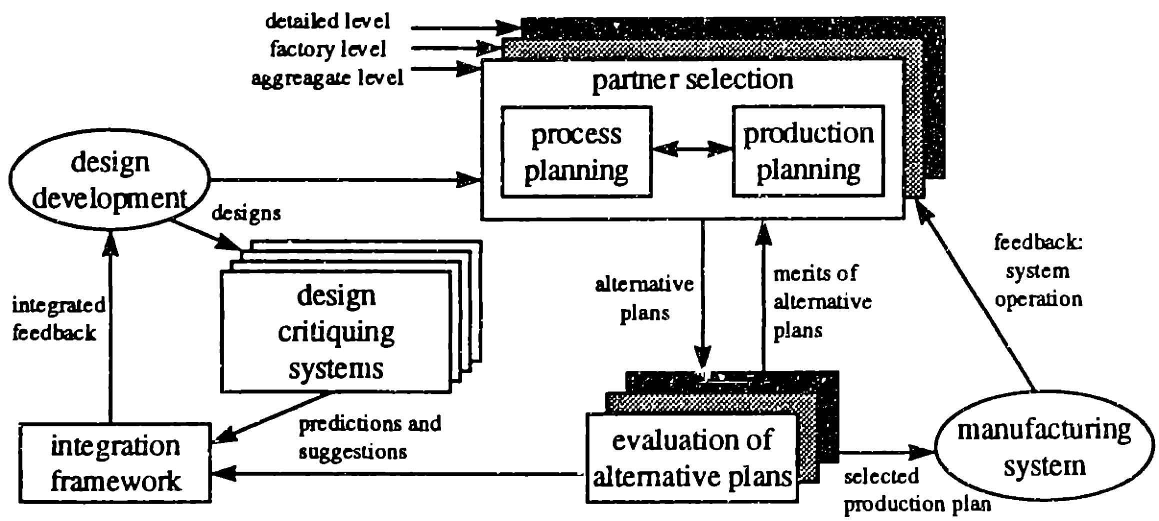


Figure 3.2.2-3: Institute for Systems Research Integrated Virtual Factory Toolkit Model

Source: *Virtual Factories for Electro-Mechanical Device Manufacturing*, NASA Tech Briefs, July 1996.

3.1.3.3 Government-Industry-University Partnerships—The TeleCom℠ City Project

Government-Industry-University Partnerships are a significant component of the new initiatives to reduce costs through innovative infrastructure reform. Currently in it's birth stage, the TeleCom℠ City Project is an example of the type of joint venture which will bring the technology interests of the government and industry in line with the resources of universities and society.

TeleCom ℠ City is a $750 million collaborative regional technology development initiative which will combine the resources of Massachusetts industry, universities, and government to establish the region as a major entity in the telecommunications arena. Its mission is to support to companies, universities, and government institutions engaged in research, development, and production of cutting-edge telecommunications and related technologies, products and services [53]. Currently, TeleCom℠ City is in its initial concept stage and has received widespread support and substantial financial commitment from Massachusetts government. Rapid advances in digital voice, image, and data transmission have begun to blur the distinction among the types of telecommunication services and the companies responsible for providing them. TeleCom℠ City is aimed at providing a central utility to accelerate product development through high value-added advanced design, testing, prototyping, and manufacturing.

Located just a few miles from the campus of MIT, the TeleCom℠ City project will occupy over 200 acres overlapping three Massachusetts communities—Everett, Malden, and Medford—and is expected to establish a new model of cost-efficient socially-aware business operation. Refer to Exhibit 3.1.3.3-1. The project will eventually bring 10,000 permanent highly skilled jobs to the region. TeleCom℠ City is uniquely focused to provide a partnership among university research and the interests of the private sector in applied research, product development, and commercialization. Through a collaborative effort, TeleCom℠ City will serve as a chief resource for bridging the gap between expertise of university faculty and graduate research with current and future industry needs. The project supports cost-efficient outsourcing of basic research for advanced telecommunications technology product development from companies to universities, introducing a higher degree of corporate flexibility for committing capital resources to short-term endeavors. Plans include 3,000,000 square feet to be developed during an initial phase with facilities for research and development laboratories, offices, manufacturing and assembly, fiber optic infrastructure, and KU and C band international and domestic satellite stations.

Senator Kerry, MIT Officials Join Mayors on TeleCom℠ City [29]

Massachusetts Senator John F. Kerry was responsible for initiating one of a series of recent strategy meetings to discuss the TeleCom℠ City project, bringing together representatives of Senator Edward Kennedy and Congressman Edward J. Markey; the Mayors of Malden and Everett Massachusetts; and a distinguished group from MIT that included President Charles Vest, Provost Joel Moses, Dean of the School of Architecture and Planning William Mitchell, Dean of Science Robert Birgeneau, Dean of the Sloan School of Management Glenn Urban, Director of the Laboratory for Computer Science Michael Dertouzos, and Media Lab Director Nicholas Negroponte.

Senator Kerry discussed the changing role of federal research and its impact on universities and industry. He addressed the opportunity to attract new industrial research and expansion into the technology base of the Massachusetts economy through TeleCom℠ City. Kerry also talked about MIT's possible collaboration and shaping of this important regional economic development initiative as a part of their mission of education and entrepreneuralism. City of Everett Mayor John R. McCarthy discussed the role of TeleCom℠ City in revitalizing older urban communities, such as Everett, Malden and Medford. He said that TeleCom℠ City is a unique regional technology development initiative with state and national implications. "TeleCom℠ City will be a model of how mature urban areas collaborate to expand their tax base and create jobs." An action plan was presented in the meeting that included the suggested role of MIT, the appointment of an MIT/TeleCom℠ City liaison, and MIT's participation in a Scientific Advisory Committee and the TeleCom℠ City Development Task Force.

Exhibit 3.1.3.3-1: TeleCom℠ City—A Model for Government-Industry-University Partnership

Source: "Senator Kerry, MIT Officials Join Mayors on TeleCom℠ City, *Everett Leader Herald*, 1 August 1996

3.2 Candidate Technologies for the Multi-Product Adoption Model

"To enable" means to make possible, practical, or easy. A "technology" is an applied science or a technical method of achieving a practical purpose. "Enabling technologies," therefore, are the scientific advancements which are directly responsible for providing a practical ability to gain measurable increases in operation, functionality, efficiency, or performance from physical systems. A natural aggregation of enabling technologies yields two fundamentally distinct types—those which enable products, and those which enable processes.

In the examples presented to illustrate the multi-product adoption model, a particular enabling technology has been selected from each of the two types—products or processes. Modern multivariable control theory enables the "process" of designing practical controllers to achieve unprecedented high precision performance from physical systems. Advanced radar and infrared sensor technology provides the "product" components which offer significantly enhanced signal integrity and noise isolation over previous generations. The objective of this section is to indicate the significance of modularity, portability, and transferability in developing dual-use enabling technologies.

3.2.1 Optimal Robust Real-Time Multivariable Control

Developments in advanced mathematics, operator theory, multi-dimensional optimization methods, neural networks, fuzzy logic, and applied optimal control theory have introduced the present generation of control system technologists to a world of new options over conventional servo-based design techniques. A wide range c.' applications for control system synthesis and optimization exist in today's marketplace. General examples of products with controllers include home appliances, heating and cooling systems, computer disk drives, stereo components, automobiles, aircraft engines, industrial process control systems, and factory automation, among many others. Virtually all electro-mechanical devices have some type of control system which governs the state of the machine during operation. A general discussion and several case study examples are used to illustrate the application of the multi-product technology adoption model to practical real-time control system design. This discussion emphasizes the development of structured and automated control system design processes with specific application to missile flight dynamics, steering control system design for an automated highway system, and robust process control for distillation systems.

Beyond the evolution from classical servo-control systems design to multivariable state space approaches, there now exists a wide spectrum of techniques and approaches which can be selected depending on the nature of the specific objectives for the control problem. Feedback linearization, model-reference adaptive nonlinear control, and the so-called "post-modern" approaches to robust control system synthesis/design present powerful mathematical approaches to optimized solutions of control and estimation applications. Using many of these recent techniques and the numerical methods which have been realized in many commercially available software packages, the control system designer has the ability to incorporate robustness to parametric uncertainty directly into the controller synthesis problem formulation and design optimal real-time controllers.

In short, today's control system designer is presented with a comprehensive toolbox of methods and approaches to solving almost any physical dynamic controls problem assuming the dynamics can be mathematically modeled, states can be measured or estimated in real-time, and sufficient resources are allocated for synthesis, analysis, integration, and test of the physical system. A general process for control system design includes concept development, detailed design, simulation, hardware-in-the-loop testing and validation, and final implementation. Accelerated development and cost efficiencies can be achieved by reducing the total time and/or resources required to complete these steps.

Using case study examples, this thesis illustrates how the same technical methodologies for developing a missile autopilot control system can also serve as the model for designing controllers for a wide set of applications. What is being treated here as a candidate for dual-use technology is the control system synthesis methodology, not the actual microprocessor-based controller implementation itself. So, this section introduces a technology which enables the "process" of achieving robust control design, and the next section introduces an enabling technology which is a "product" component which can be directly inserted or tailored to particular target applications.

In the development of the control system design examples, the selection of linear quadratic and H-Infinity/Mu-Synthesis methodologies represents just two of the many techniques available. The choice of control system design approach is left to the designer and should be based on the particular type of application and specific objectives of the system to be designed.

3.2.1.1 Optimized Multivariable Autopilot Control System for a Highly Agile Interceptor

The ability to defend an asset area against current threat capability, including tactical ballistic missiles and low-altitude cruise missiles, represents a paramount challenge for present military applications. Next generation missile interceptors require technology to defeat faster, more maneuverable, extremely low-observable targets. Figure 3.3.1.1-1 illustrates a representative engagement geometry for the missile interceptor problem. The common analogy for this type of precision flight control for guidance to intercept is the "bullet hitting a bullet" scenario. With the simultaneous demand for reduced life cycle cost and a "one-target one-weapon" direct-hit philosophy, structured methods to automate "batch-designing" high precision optimized controllers are very desirable and have been demonstrated with a high degree of success [24,55,57]. This case study analysis presents the application of modern control theory methods to the missile interceptor problem. Technical details of the controller architecture and target maneuverability have been neglected to avoid proprietary and security classification issues. A functional block diagram of the missile-target intercept flight control strategy is illustrated in Figure 3.3.1.1-2.

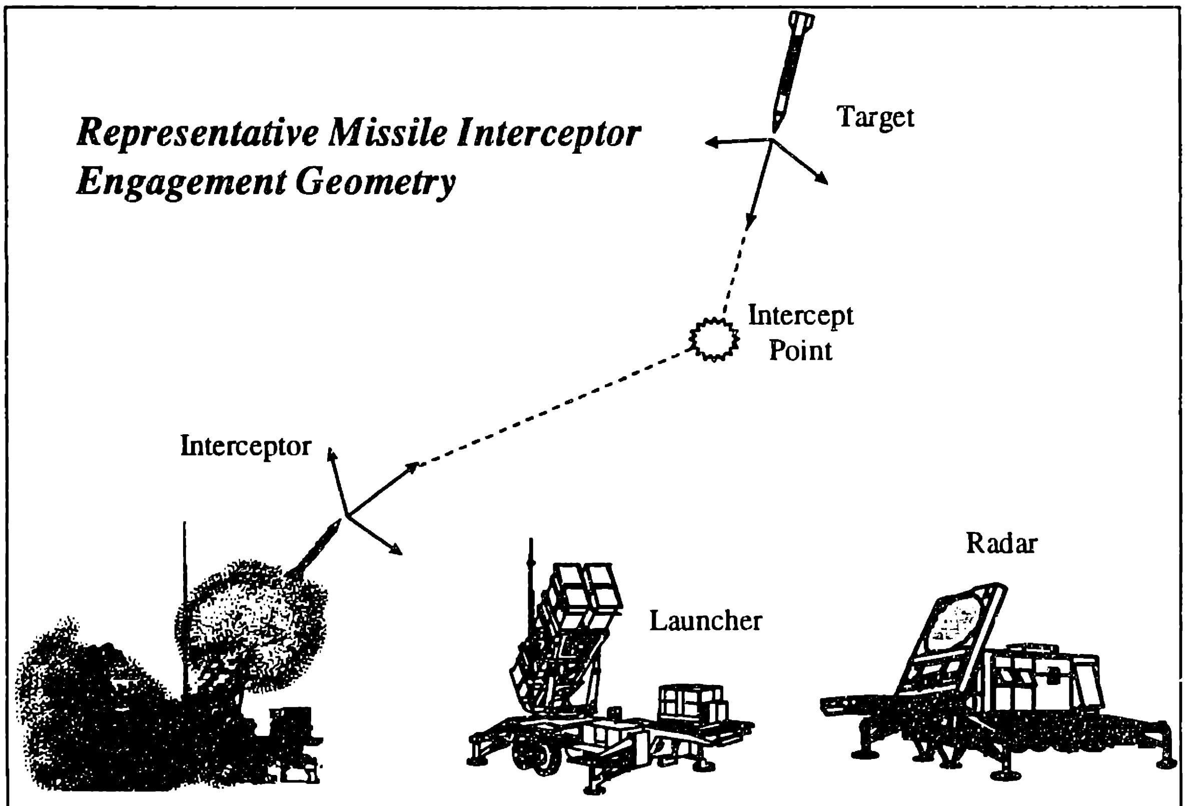
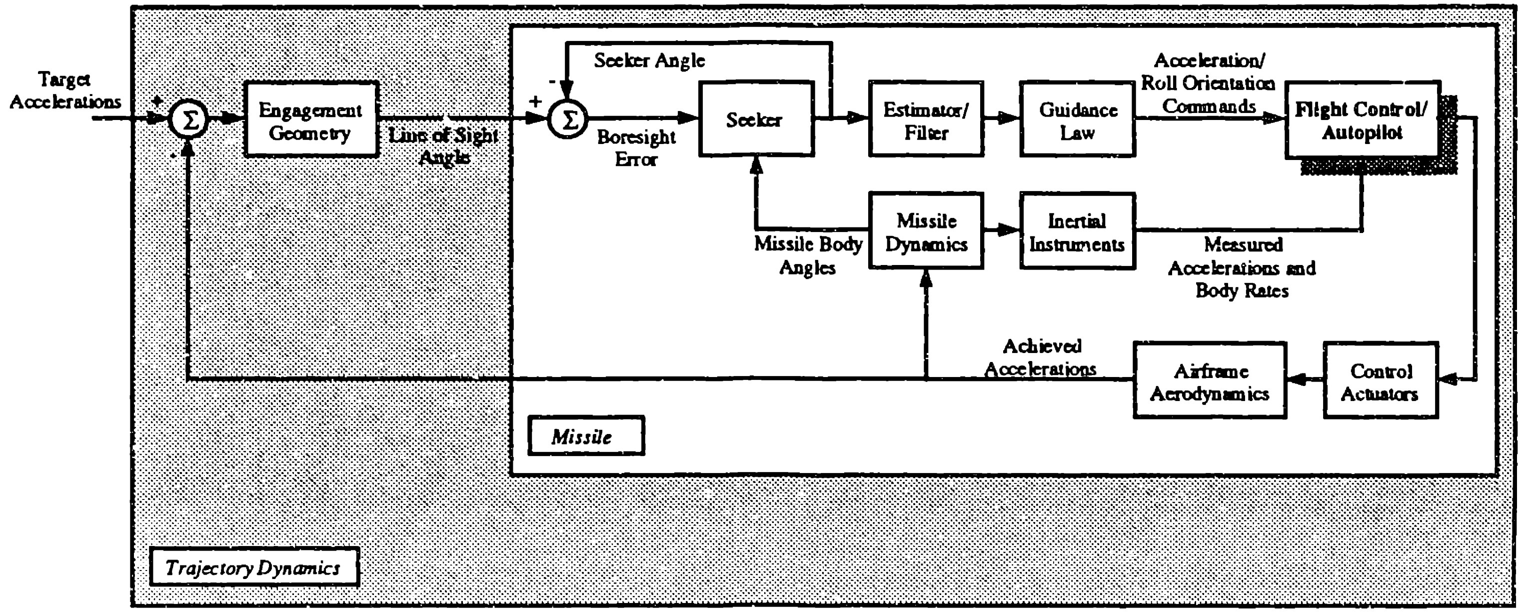


Figure 3.2.1.1-1: Missile Interceptor Control Problem Representative Engagement Geometry



- **Autopilot Plays a Critical Role in Providing Stable Robust Controlled Missile Flight Dynamics to Achieve Intercept**
- **Multivariable Autopilot Exploits Multi-Loop Stability and Optimizes Closed Loop System Performance**

Figure 3.3.1.1-2: Overview of Missile-Target Intercept Flight Control Strategy

Missile flight dynamics are described by a set of coupled differential equations based in a three axis orthogonal system—pitch, yaw, and roll. Representative dynamics can be modeled using traditional missile airframe derivations outlined in [27]. The complexity of the control problem is dictated by the 3-plane geometric flight mechanics relationships. Cross-coupling effects result from the inertial linking of the missile rectilinear motions and rotational dynamics and aerodynamic coupling inherent to the airframe. In this formulation, the section of the flight control system which stabilizes the airframe and provides omni-directional lateral acceleration command tracking while simultaneously controlling roll orientation is defined as the autopilot. Refer to Figure 3.3.1.1-2.

One general approach employed by many classical skid-to-turn flight control designs is to include a disturbance rejection roll autopilot which attempts to decouple the lateral airframe dynamics from roll with fast roll response and higher bandwidth in roll than in pitch/yaw. Laterally induced roll rates are forced to zero before being fed back to the pitch/yaw axes. Since classical designs do not directly address cross-coupling, stability considerations limit roll bandwidth which constrains pitch/yaw bandwidth so performance and robustness inevitably suffer. In response to increasing threat maneuverability, reduced homing time, and low observable targets, this design methodology combines recent developments in digital sensors and signal processing with a multivariable autopilot to collectively stabilize the airframe and achieve direct cross-coupled control of the flight dynamics. Because the multivariable concept exploits cross-coupled control, pitch/yaw bandwidth is not necessarily dictated by the roll channel and enhanced cross-coupling compensation is implicit to the control structure.

Although missile dynamics are nonlinear and the actual flight control implementation includes mild nonlinearities such as limiters and switching logic, linear design techniques and gain-scheduling are generally applied for autopilot synthesis primarily due to the extensive powerful mathematical methods available for linear control system design. The basic advantage behind the application of optimal linear multivariable control theory to autopilot design is an exploitation of achievable stability in a multi-loop sense. It is the implicit stability that leads to potential improvements in system tracking performance. Since every physical control system presents a fundamental trade-off between stability and performance, the level of achievable stability defines a bound on realizable performance. Modem multivariable methods optimize performance by delivering robust multi-loop stability with the capability for tighter tracking than classical designs of the same bandwidth. Gain-scheduled linear control of nonlinear systems has been demonstrated with classical designs as an effective means of governing complex physical system behavior [24,44,55,57,62,83]. Modern control approaches generally include a performance index or cost functional which introduces a notion of optimality to the control system design problem formulation (actually, a more appropriate term perhaps is *suboptimality* for the case of restricting synthesis methodologies to linear control of nonlinear systems).

Multivariable control system design presents the capability to widen the operational performance range of tail-controlled missiles. Optimal linear multivariable autopilots can stabilize missile dynamics at higher angles of attack, and wider regions of operation, than classical servo-feedback designs. Therefore, comparing multivariable autopilot characteristics to existing classical designs not only includes enhancements in missile response time, stability, and robustness, but also must include discussion about additional measures of autopilot performance sometimes considered to fit outside the functional scope of the autopilot design—maximum g-limit acceleration before stress shear of the airframe, command slew rate limits, gravity compensation, and kinematic coupling compensation.

Modern multivariable linear optimal control theory offers alternative formulations to achieve different objectives depending on the particular application. Associated with each design approach is an optimality condition based upon a weighted combination of system parameters (typically including measured outputs, estimated states and/or control authority). A number of approaches exist, but the two techniques chosen for presentation of the missile autopilot control system design presented here are linear quadratic (LQ) and H-Infinity/Mu-Synthesis. For a top-level assessment selected autopilot design techniques, refer to Figure 3.3.1.1-3 and Figure 3.3.1.1-4.

These brief discussions are intended only to define the fundamental concepts used in developing the optimal control problem formulation and are by no means a rigorous mathematical treatment of the underlying theory. It is assumed that the reader is familiar with signals and systems, control theory, and finite dimensional vector space mathematics. For a more detailed presentation of this material the reader is directed to the attached list of references.

A Historical Perspective of Control System Design

- Classical Control (Pre-1960s)
  - Single Input Single Output
  - Frequency Domain Formulation of the Control Problem
  - Analysis Techniques Include Nyquist, Bode, Root Locus, etc.
  - Controllers are generally of pre-specified order/structure (e.g. PID)

- Modern Control (Early 1960s to Present)
  - Multiple Input Multiple Output
  - Time Domain Formulation of Control Problem
  - Analysis and Synthesis Techniques Include a Notion of Optimality
  - Linear Quadratic Methods, Loop Recovery, etc.

- Post-Modern Control (Mid-1980s to Present)
  - Input / Output Approach to Control System Analysis and Design
  - Exploits Properties of Signal and System Norms and Induced System Gains
  - Introduction of Functional Analysis, Small Gain Principle, Coprime Matrix Factorization, and Operator Theory to Robust Optimal Linear Control System Analysis, Synthesis, and Design
  - Development of H2, H-infinity, μ, Mixed H2/H-infinity, L1 Control Theory
  - Rigorous Mathematical Handling of Linear Time Invariant Complex/Real Parameter Uncertainty (H-infinity/μ)

Figure 3.3.1.1-3: Control System Design Evolution

Control Methodology	Advantages	Disadvantages
Classical Methods	• Stabilize plant dynamics • Command tracking capability	• Single loop design • Limited cross-channel control/stability
Linear Quadratic Regulator	• Guaranteed multi-loop stability • Accurate multi-command tracking • All implementation issues resolved	• Additional controller complexity • High throughput/memory requirement relative to classical designs
H-Infinity/μ-Synthesis	• Achieves multi-loop stability • Accurate multi-command tracking • Natural framework for directly accounting for time-varying or other parameter uncertainty during synthesis procedure • Optimal stability/performance and robustness to expected *worst case* perturbations and/or uncertainty.	• Additional controller complexity • High throughput/memory requirement relative to classical and LQR designs • Desired constraints on time response characteristics must be approximated by mapping to frequency domain • Some implementation issues unresolved

Figure 3.3.1.1-4: Top-Level Assessment of Selected Autopilot Design Approaches

An Automated LQR Design Process Using Multidimensional Optimization

Linear quadratic regulator (LQR) design has been developed as a practical means of multivariable autopilot design and implementation for many years in academics and industry. LQR control design can be used to achieve desired low frequency performance, then augmented by digital gain-stabilizing structural/noise filters to achieve high frequency stability to flexible body characteristics and unmodeled dynamics and to provide attenuation of noise transmission to control actuators. Linear Quadratic (LQ) optimal control minimizes an infinite time integral cost functional in which the relative importance of the system states and controls are traded off against one another. In the context of the missile autopilot design, the trade-off is formulated among lateral acceleration rise time and overshoot, actuator rate limits, bandwidth and stability margins, cross-coupling disturbance rejection, and sensor-to-control noise propagation. Inherent properties of LQ full-state feedback include guaranteed closed loop asymptotic stability with ample gain and phase margins for digital implementation. Although LQR asymptotic properties rely on full-state feedback while the actual system will inevitably have unmodeled dynamics which may reduce stability margins, proper bandwidth limitation can ensure a robust feedback control implementation [24,44,55].

Most fundamental to achieving desired closed loop command following response from an LQR controller is the selection of state and control weighting matrices. As opposed to conventional single loop design methods which typically employ pole placement techniques or other heuristic methods, the LQR formulation is analytically solved in the time domain and the state and control weighting matrices define the relative scaling among system parameters. Due to the high dimensionally of the problem, weighting function selection is most efficiently solved using automated optimization techniques. Possibilities include grid-search, trial and error, steepest descent gradient techniques, and even neural networks. One of the most promising techniques for automating the LQR gain design process for missile autopilot controller synthesis has been developed from a nonlinear multi-dimensional constrained numerical optimization approach using functions from the MATLAB® Optimization Toolbox. Once appropriate weighting parameters are selected, the LQR controller is generated, discretized, and evaluated using full-spectrum (over full range of Nyquist frequency) high fidelity discrete linear/tolerance analysis tools.

Trim Point linearization is the process of determining an equilibrium point in the nonlinear differential equations which describe the missile flight dynamics. At a fixed instant in time, a combination of fin displacements can be determined which results in zero net sum moments on the body. The equilibrium point is referred to as a trim condition and small perturbations of the differential equation state variables yield a set of linear dynamic equations representative of the local nonlinear operating condition. Using this linearization approach, gains can be calculated over sets of operating conditions and scheduled during flight to accomplish robust control of the missile trajectory dynamics. A Coupled Linear Dynamics (CLD) program solves for a combination of fin displacements to achieve trim. A standard 5-state linearized airframe state space model [27] is calculated at trim by the CLD program. The airframe model is augmented with first order lags representative of the actuator delay over the autopilot bandwidth. A transformation of measured outputs from inertial instruments to modeled states completes the construction of a full-state feedback LQR formulation for the low frequency state components of the control system.

Full-spectrum discrete linear time and frequency response analysis of the autopilot implementation is evaluated with the CLD airframe and high fidelity simulation models of the flexible body dynamics, tail-wags-dog effects, actuators, sensors, and digital gain stabilizing structural/noise filters. LQR can thus be used as a design methodology with actual implementation not truly requiring full-state feedback (excluding states which are either unavailable such as the high frequency flexible body dynamics or are accompanied by excessive measurement noise such as the achieved fin angular deflections/rates). Although the implementation is not actually full-state feedback, the derivation presents the practical application of a powerful LQR optimal design approach to enhancing missile system stability, robustness, and performance.

The LQR gain design optimization procedure is illustrated in a flowchart in Figure 3.3.1.1-5. This nonlinear multidimensional constrained optimization procedure has been developed using quadratic sequential programming techniques to converge to a locally optimal solution. Comparison of the local optimal to benchmark nonlinear results which bound true system performance yields a process metric to guide decisions on acceptable optimization solution convergence. A similar procedure has received company-wide recognition for realized cost reductions through acceleration and automation of a major contributor to the nominal product development cycle for missile flight control systems. Perhaps the most significant contribution is the portable and transferable nature of the design process. The same process can be applied to any number of control problems which can be treated similar to autopilot synthesis, including industrial process control and automated highway system steering control.

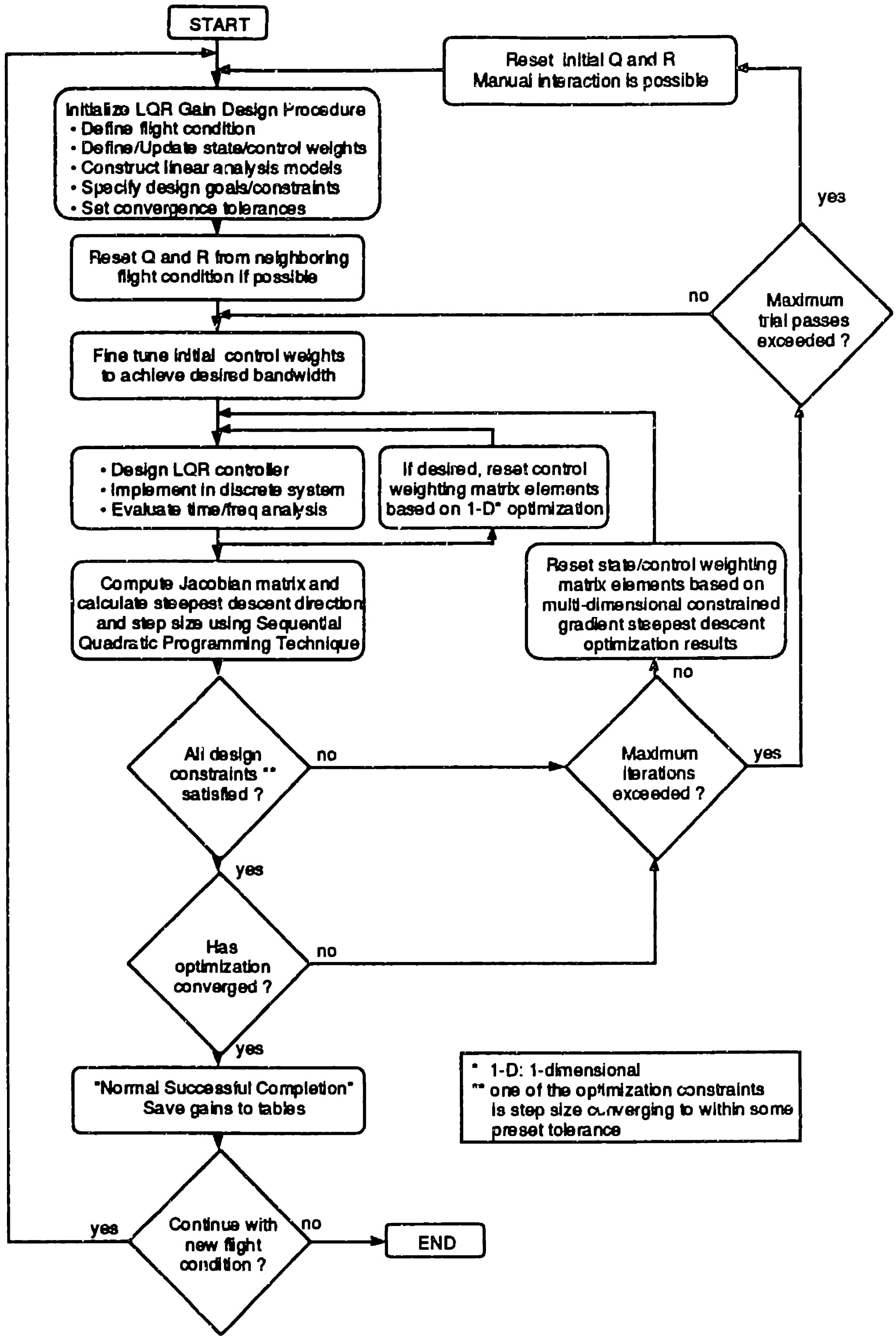


Figure 3.3.1.1-5: LQR Multidimensional Optimization Process Flow

Relating H-Infinity/μ-Synthesis to Conventional Control System Design

Classical methods for control system design achieve satisfactory stability and robustness to time-varying properties by inevitably sacrificing time response performance. Advances in digital sensor technology have aided the successful design and implementation of classical controllers to provide adequate stability and control over multivariable physical systems. Developments in applying finite dimensional vector space mathematics and linear systems theory to practical control problems have yielded modern time domain state space tools for control system design. Employing state space techniques, there is a straightforward generalization of single command tracking systems to multiple command tracking systems with complex interactions between modeled dynamics and competing design objectives.

In order to apply classical methods to a multiple-input multiple-output (MIMO) problem, the physical system dynamics and design objectives are typically decoupled with independent classical controllers designed to provide single-input single-output (SISO) stability and performance. The SISO designs are implemented in parallel and evaluated with the coupled MIMO system model. If the plant dynamics are significantly coupled, the classical design implementation may require cross-coupling compensation or increased bandwidth to maintain the intended robust stable performance and to achieve satisfactory disturbance rejection. Modern multivariable control theory attempts to solve the MIMO problem by implicitly addressing plant cross-coupling with multivariable cross-coupled control.

With the development of modern control theory and practical design/implementation of multivariable controllers, a need arises for expanding the classical notion of stability. Classical SISO stability analysis can be characterized with fair completeness by either Bode responses or any of a number of classical tools, all of which are based on the Nyquist stability criterion. MIMO systems have introduced higher dimension to the concept of linear stability. Typically, the stability of a SISO control system can be characterized by breaking the feedback loop(s) at the control input(s) and evaluating gain and phase margins, crossover frequency, and the level of high frequency attenuation where unmodeled dynamics exist and noise transmission is intended to be suppressed. Although it is still useful to measure single loop stability with MIMO systems, there is an additional issue of breaking more than one loop simultaneously and evaluating *multi-loop* stability. This issue has been addressed with a vector generalization of classical Bode magnitude stability analysis developed from a multivariable version of the Nyquist stability criterion known as singular value analysis. Singular value analysis is essential in the development of the H-Infinity/μ control problem; derivation of concepts can be found in [4,19,20,21,22,51].

Recent developments in H-Infinity/μ-Synthesis linear control theory have provided a means of designing controllers which minimize the weighted maximum Structured Singular Value (SSV or μ) of linear systems. The methodology is based on input/output signal relationships and controllers are synthesized using a weighted system norm approach. The H-Infinity/μ-Synthesis control problem formulation is developed and solved analytically in the frequency domain, reminiscent of classical design techniques. A driving theoretical conclusion and necessary foundation for the derivation H-Infinity/μ-Synthesis control is the Small Gain Theorem—a multi-loop vector generalization of the single-loop traditional Nyquist stability criterion, the basic premise behind all classical control theory including the analysis methods of Bode, Hurwitz, and Nichols. In this respect, H-Infinity/μ control revisits some fundamental frequency domain concepts and involves multi-loop generalizations of many classical design techniques.

One distinct advantage of the H-Infinity/μ-Synthesis formulation is its natural framework to parameterize uncertain characteristics in the system with robustness to such perturbations accounted for directly by the controller design methodology. However, increased robustness to parameter variations is typically achieved over other approaches at the cost of additional compensator complexity and increased throughput requirements. For some applications, particularly if the system dynamics are well known, achieving robust stability in the presence of unmodeled or time-varying dynamics may be accomplished at the expense of an inability to maintain nominal time response characteristics including closed loop overshoot and damping over multiple simultaneous perturbations such as those encountered with maintaining missile stability/performance over regions of neighboring operating conditions.

The H-Infinity approach is complimented by a natural extension to linear fractional transformations (LFTs) and structured singular values (SSV or μ) which provide a framework to rigorously treat system perturbations in the optimal linear controller synthesis. Advancements in applying LFTs to the H-Infinity problem formulation and numerically calculating bounds on μ has brought H-Infinity/μ-Synthesis from a post-modern frequency domain analytical design framework to a practical design tool. In the H-Infinity problem formulation, a pair of algebraic Riccati equations similar to that of Linear Quadratic theory is derived whose non-unique solution can be parameterized by a scalar value (γ) which results in an upper bound for the weighted system maximum unstructured singular value over all frequency. Using this derivation with an extension to *structured* singular values, a scheme has been developed to iteratively solve for the minimization of the maximum weighted structured singular value μ [4]. The μ-Synthesis and Analysis Toolbox developed by MUSYN® for MATLAB® has functions implemented to compute the centralized solution of the Youla-parameterization of all dynamic compensators which satisfy the H-Infinity optimization. As with LQR theory, H-Infinity/μ-Synthesis techniques are applicable to the analysis, synthesis, and design of multivariable control systems including application to missile autopilots.

Steps in solving any practical control problem include modeling relevant system dynamics and the formulation of stability, robustness, and performance objectives to produce a design approach which yields numerically solvable equations. H-Infinity/μ-Synthesis control system design is formulated by constructing a *generalized plant model* which incorporates weighting functions to characterize desired closed loop behavior of selected system signals. Weighting functions are designed as a direct mapping of system stability, robustness, and performance objectives by assigning scaled frequency dependent penalties to selected signals. For simple systems with few objectives such as low order SISO systems, weighting function design is very straightforward. For highly dimensioned systems with multiple competing (sometimes conflicting) objectives and constraints, the complexity involved in design of weighting functions grows quickly, analogous to any multi-objective constrained optimization problem.

In the H-Infinity/μ-Synthesis context, weighting functions are used to impose performance specifications, model physical limits of the CAS, bandlimit expected disturbance signals, and characterize airframe parameter uncertainty. Weighting functions generally belong to the set of stable rational proper transfer functions to be consistent with assumptions made in the Algebraic Riccati Equation solution to the H-Infinity control problem. A generalized plant model for H-Infinity/μ-Synthesis multivariable autopilot design is given in Figure 3.3.1.1-6 followed by an explanation of the perturbation model included in the figure.

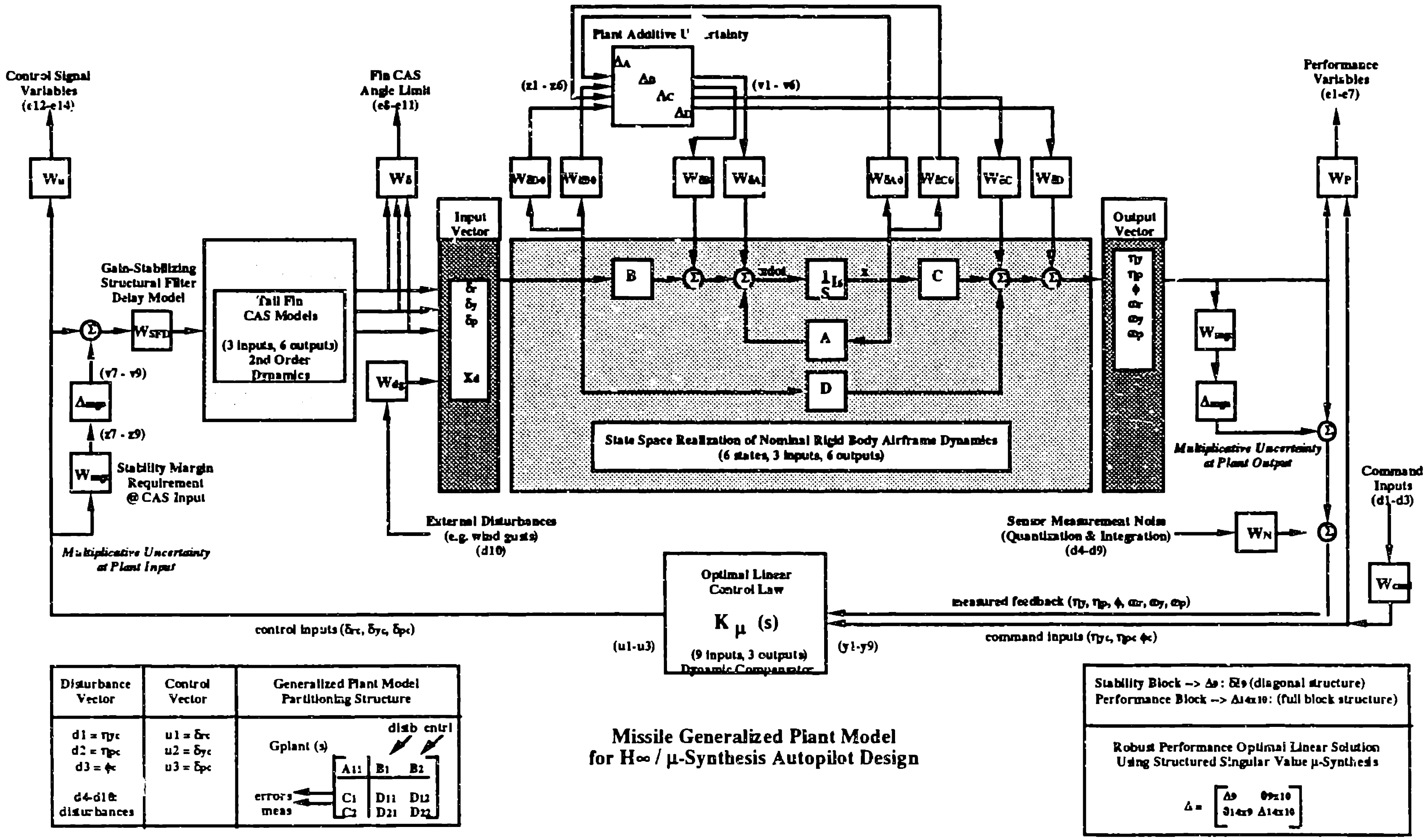


Figure 3.3.1.1-6: Representative Generalized Plant Interconnection Model for Missile Multivariable Autopilot Design Using Mu-Synthesis

H-Infinity/μ-Synthesis Perturbation Model Discussion

In the block diagram illustrating the generalized plant model given in Figure 3.3.1.1-6, a 5-state realization of the linearized rigid body airframe dynamics plus a 6th state representing integrated roll rate is augmented with second order dynamics for three effective tail fin actuator models—pitch, yaw, and roll. Weighting functions are used to reflect command tracking performance objectives and impose constraints representative of mechanical saturation of the control actuators. Additive uncertainty is modeled to represent real and complex parametric changes in the linearized airframe state matrix elements. High frequency stability to unmodeled flexible body structural dynamics is accomplished with multiplicative input and output uncertainty. For practicality, the additive uncertainty can be treated as a complex valued full block structure summed across the entire nominal state model of the airframe.

The perturbation model includes the modeled parametric uncertainty, requirements on stability and robustness, and desired command tracking performance objectives. Nominal design requirements include performance objectives and physical constraints on the state and control variables. Specifications for the H-Infinity/μ-Synthesis design have been defined based on the requirements and constraints outlined in the introductory sections of this report. Basic requirements as summarized below can be used to establish weighting functions for H-Infinity/μ multivariable autopilot synthesis. Related H-Infinity/μ optimization weighting functions referred to in Figure 3.3.1.1-6 are given in parenthesis for each performance/design objective.

Performance Objectives:

- Provide robust stability and performance over a specified region of operation (collective set)
- Optimize time responses in achieving lateral acceleration and roll angle commands (Wp)
- Maintain less than 10% overshoot in lateral and roll step responses (Wp)
- Achieve lateral acceleration steady state tracking error to within 1% (Wp)
- Achieve roll angle steady state tracking error to within 1% (Wp)
- Induced transient roll rate due to lateral maneuver constrained to not greater than 15 deg/sec/g (Wp)

Design Constraints:

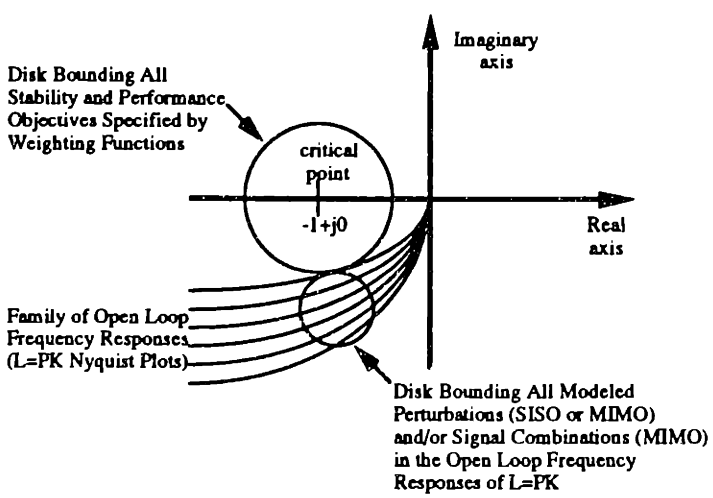
- Achieve simultaneous pitch-yaw-roll command following without control saturation (Wu)
- Constrain system bandwidth for high frequency stability and noise attenuation (Wu, Wmgn, Wp)
- Provide single loop phase/gain margins of 6 dB and 30 degrees at controls and sensors (Wmgn)
- Account and compensate any unmodeled high frequency dynamics (Wu, Wmgn)
- Minimize kinematic and aerodynamic cross coupling disturbance effects flight maneuvers (Wp)
- Maintain vehicle operation to within inertial instrument measurement dynamic range limits (Wp)
- Sufficiently limit body rates to avoid excessive disturbance to seeker torque motors (Wp)

Nominal linearized rigid body airframe dynamics are defined by the state model equations described in the equations below. Effects due to uncertainty in any of the elements of the state equations can be included by augmenting the state matrix equations as indicated.

$$dx(t)/dt = Ax(t) + Bu(t) \qquad \textit{Nominal Plant}$$
$$y(t) = Cx(t) + Du(t)$$

$$dx(t)/dt = [A+[W_{\delta A}][\Delta A][W_{\delta A0}]]x(t) + [B+[W_{\delta B}][\Delta B][W_{\delta B0}]]u(t) \qquad \textit{Generalized Plant}$$
$$y(t) = [C+[W_{\delta C}][\Delta C][W_{\delta C0}]]x(t) + [D+[W_{\delta D}][\Delta D][W_{\delta D0}]]u(t)$$

A comprehensive additive uncertainty block structure can be defined generically as Δ which incorporates all of the elements of the perturbation state matrices ΔA, ΔB, ΔC, and ΔD and the associated weighting function matrices $[W_{\delta A}]$, $[W_{\delta A0}]$, etc. This structure conservatively represents the perturbation model at neighboring conditions or under time-varying environmental/hardware changes such as actuator heating. Since most nonlinear aerodynamic models have been generates based on comprehensive wind tunnel test data, the force and moment coefficients are assumed to be known with fair certainty. Parameter uncertainty is modeled mainly to represent perturbations in operating condition and/or fin effectiveness. Since all of the aerodynamic stability derivatives in the linearized state equations change value with respect to dynamic pressure, angle of attack, and wind angle, these perturbations about the nominal are modeled as well. Together with the design objectives for nominal stability and performance, the uncertainty model is incorporated to encompass the most parasitic combination of parametric variation expected during operation. This design methodology accounts for all of the modeled phenomena. A graphical interpretation from a multivariable Nyquist perspective is given in Figure 3.3.1.1-7.



Note: H_∞/μ design objective is to insure that no member of the complex-valued frequency responses bounded by the perturbation disk intersects any region bounded by the stability/performance specification disk.

Figure 3.3.1.1-7: Graphical Interpretation of H-Infinity/μ–Synthesis Autopilot Design

Example weighting functions are illustrated in Figure 3.3.1.1-8 and Figure 3.3.1.1-9. A tailored QFD House of Quality analysis compares LQR and H-Infinity/μ in Figure 3.3.1.1-10.

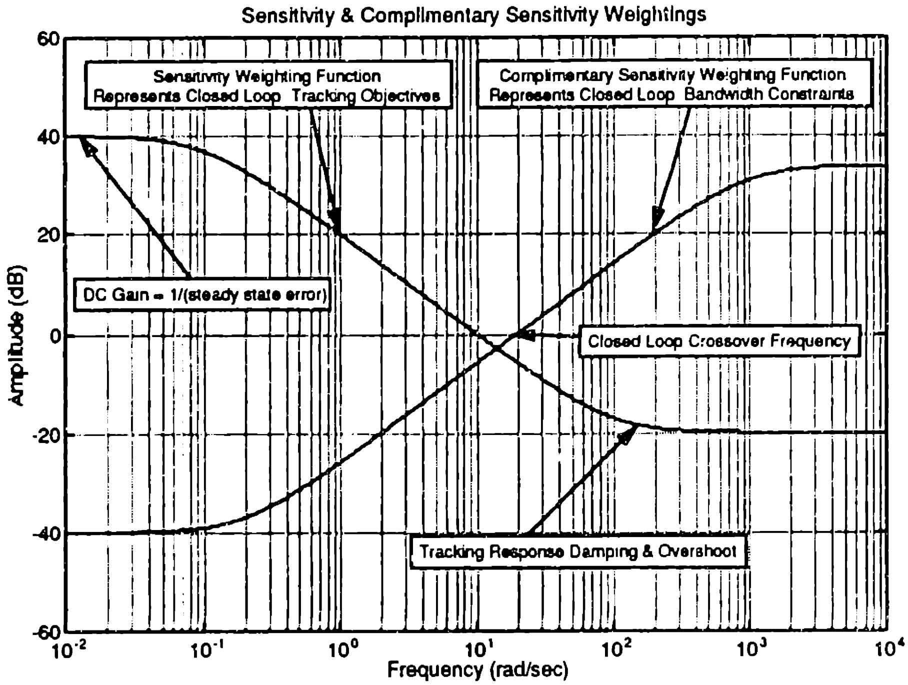


Figure 3.3.1.1-8: Sensitivity and Complimentary Sensitivity Weighting Functions

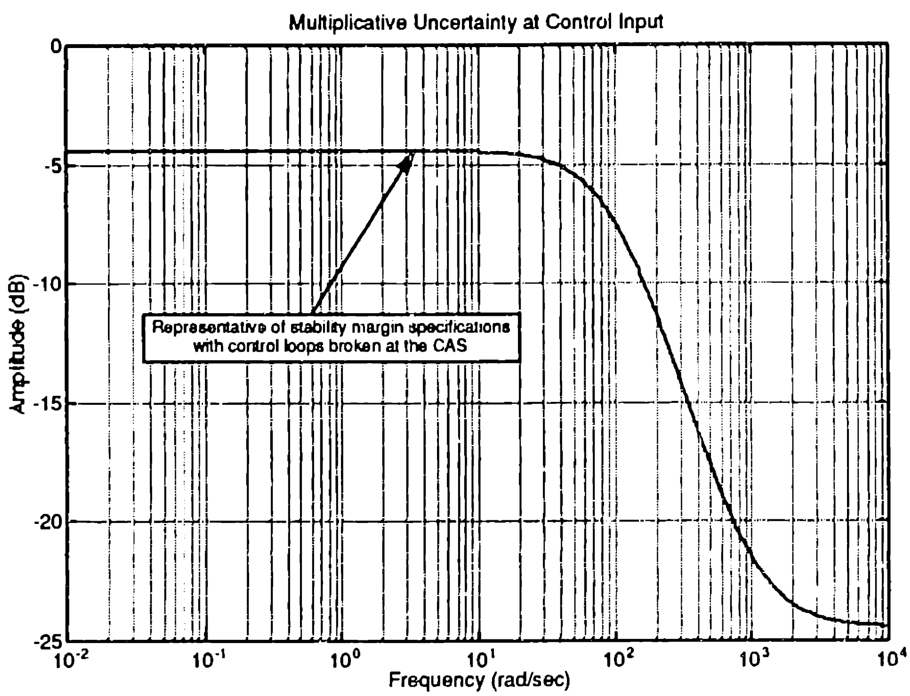


Figure 3.3.1.1-9: Multiplicative Uncertainty at Control Input Weighting Function

Tailored Quality Function Deployment (QFD) House of Quality (HoQ) for Multivariable Autopilot Design			Engineering Characteristics: Linear Response Time Constant τ63			Overshoot			Open Loop Bandwidth (ωcr)			Gain Margin @ Control Actuators			Phase Margin @ Control Actuators			Gain Margin @ Sensors			Phase Margin @ Sensors			SSV
	Weighting Factor	Normalized Weight	Pitch	Yaw	Roll	Pitch	Yaw	Roll	Pitch	Yaw	Roll	Pitch	Yaw	Roll	Pitch	Yaw	Roll	Pitch	Yaw	Roll	Pitch	Yaw	Roll	Small Gain Theorem
Autopilot Design Attributes																								
Time Domain Performance																								
Fast Response																								
Small Planar Steps	5	7%	●	●	●	□	□	□	x	x	x	□	□	□	x	x	x	x	x	x	x	x	x	O
Large Planar Steps	4	5%	●	●	O	□	□	□	x	x	x				□	□		□	□	□	□	□	□	
Sinusoidal Planar Input	2	3%	O	O	O	□	□		□	□		□	□		□	□								●
Multiple Channel Tracking	5	7%	O	O	O	O	O	O	x	x		□	□	□	□	□	□	□	□	□	□	□	□	●
Stable Controlled Response																								
Small Planar Steps	4	5%	O	O	O	●	●		□	□	□	●	●	●	●	O	●	O	●	●	●	●	●	
Large Planar Steps	4	5%	O	O	O	●	●		x	x	x	O	O	O	O	O	O	O	O	O	O	O	O	
Sinusoidal Planar Input	2	3%				O	O	O	□	□	□													
Multiple Channel Tracking	5	7%	O	O	●	●	●	●	x	x	x													
Frequency Response																								
Stability Assessment																								
Single Loop Stability	2	3%							●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Multiple Loop Stability	4	5%							●	●	●													●
Parametric Uncertainty	3	4%							O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	●
Bandwidth Considerations																								
Low Frequency Gain	4	5%	●	●	●				x	x	x													●
High Frequency Attenuation	5	7%	□	□	□				●	●	●													●
Required Resources																								
Inexpensive Computer																								
Processing Time	2	3%							●	●	●													x
Complexity	1	1%							O	O	O													x
Memory Storage	2	3%							O	O	O													x
Inexpensive Instrumentation																								
Gyros	2	3%	x	x	x				O	O	O							O	O	O	O	O	O	O
Accelerometers	2	3%	□	□	□				O	O	O							O	O	O	O	O	O	O
Control Actuation System	2	3%	x	x	x				O	O	O	O	O	O	O	O	O							O
Other																								
Ease of Testability	5	7%	□	□	□	□	□	□	●	●	●	O	O	O	O	O	O	O	O	O	O	O	O	x
Accelerated Development Time	5	7%	□	□	□																			x
Low Risk / High Maturity	4	5%	□	□	□				□	□	□													x
sum	74	100%																						
Objective Measures	*weighted sum*		0.568	0.563	0.595	0.514	0.514	0.054	-0.54	-0.54	-0.12	0.486	0.486	0.568	0.189	0.189	0.432	0.351	0.351	0.351	0.351	0.351	0.351	0.784
Measurement Units	1 to 5	%	sec	sec	sec	%	%	%	rps	rps	rps	dB	dB	dB	deg	deg	deg	dB	dB	dB	deg	deg	deg	none
		Score	84%	84%	86%	80%	80%	45%	0%	0%	32%	78%	78%	84%	55%	55%	73%	67%	67%	67%	67%	67%	67%	100%
		Rank	3	3	2	4	4	9	11	11	10	5	5	3	8	8	6	7	7	7	7	7	7	1
Competitive Analysis — Classical			Low			Low			Low			Low			Low			Low			Low			Low
Linear Quadratic			High			High			Med			Med			Med			Med			Med			Med
H-Infinity/Mu-Synthesis			Low			Low			High			Med			Med			High			High			High

- ● Strong Positive
- O Weak Positive
- □ Weak Negative
- x Strong Negative

Figure: 3.3.1.1-10: Tailored Quality Function Deployment (QFD) House of Qual'ty for Autopilot Design

3.2.1.2 Vehicle Lateral Controller for Automated Highway System

The intention of this section is to very briefly introduce a new application for the control system synthesis procedures developed for the missile control problem. This discussion proposes the portability of these synthesis methods and identifies the dual-use nature of combining advanced control theory with automated numerical optimization processes.

A need has been identified to develop intelligent transportation systems which promise to increase capacity of existing highways by safer and more efficient use of available space. Future product development for integration with the infrastructure upgrades to support such a system includes the design of automatic steering control systems for automobiles. Controllers for this application will track the center of the lane of present travel and be capable of performing an unassisted lane change maneuver based on available information. Specialized sensors can be incorporated in future vehicle design such that accurate information can be collected about neighboring vehicles in real-time. The vehicle components and steering control system are actually local systems within a much larger possible implementation of an integrated intelligent highway system. Application of the "batch-processed" control system synthesis processes introduced with the missile autopilot to the automated steering system design is straightforward. Sensors are used for measuring outputs and estimating states in real-time and controllers are designed using automated procedures using multidimensional optimization. A study performed at Johns Hopkins University has investigated the possible application of H-Infinity control to the problem [64].

Future growth to such a system could include the incorporation of data from a central backbone which supplies information concerning current traffic patterns and congestion, road construction, delays due to collisions, etc. The development of such a system shares much common ground with many operations management techniques from production scheduling and material requirements planning for manufacturing systems to optimal networking policies for telecommunication systems. Development of core competencies in the areas of optimal control and estimation theory are directly applicable to the design of the "local controllers" required for each vehicle.

Other possibilities for application of advanced control theory include robust batch distillation column processes, manufacturing automation systems, distributed vehicles in a high performance material transfer system, achieving optimal air-fuel ratio for spark-ignition engines, and multi-objective optimization of a plastic injection molding processes, among others [23,64,88].

3.2.2 Advanced Imaging Sensors—Radar Devices and Infrared Imaging Systems

Radio frequency (RF) devices are common in many defense and commercial product technology applications including missile seekers, air traffic control, wireless telecommunications, wide area surveillance, and even microwave ovens. Infrared (IR) sensors can also be found in modern missile seekers in addition to thermographic cameras for improved night vision, bridge safety inspection, and medical product applications. Detailed discussion of radar and infrared system design has been widely documented and can be found among many references including many listed with this thesis [5,72,90]. Because such a wide scope of literature exists for RF and IR design and product applications, the discussion presented in this section focuses on several general case studies to illustrate RF and IR as dual-use or transferable technologies.

Radar systems function by detecting objects and determining their range through the reflection of electromagnetic energy transmitted and received with radio waves. Military use of radar systems is widespread for target detection and identification for ground-based systems and missile system seekers. One commercial application of radar technology is Terminal Doppler Weather Radar (TDWR) which is used to detect rapidly changing weather conditions, including wind shear and microbursts and provide this information to air traffic controllers. Wind shear is a sudden change in wind speed and/or direction that can cause an aircraft to stall or lose altitude rapidly. It poses a special hazard during takeoff and landing when planes lack the speed and altitude necessary to recover from such an encounter.

Infrared systems detect the presence of objects which emit or radiate heat relative to their surrounding environment. An example of this technology is high-resolution target tracking and identification for missiles. IR and radar have different advantages depending on the nature of the threat and the required environment for operation. Not only are IR focal plane arrays (FPAs) found aboard missiles, but also are frequently used in missile flight test equipment. Commercial applications for such products have emerged in medical markets, automated secured access systems, high-resolution bridge safety inspection, night navigation for automobiles and ships, fire detection through walls and through smoke, night safety systems for law enforcement, and night time oil spill and pollution detection.

3.2.2.1 High-Speed High-Resolution Infrared Imaging Camera Dual-Use Opportunities

This section presents a series of infrared (IR) technology applications from several sources with the intention to identify a common thread which links them all together—the core enabling IR focal plane array (FPA) technology. These applications are given as a brief description of the breadth of markets available for such advanced sensor design systems. Refer to Exhibits 3.2.2.1-1, 3.2.2.1-2, 3.2.2.1-3, and 3.2.2.1-4 for examples of the range of product applications for advanced sensor technology insertion.

New Infrared Camera Improves U.S. Navy Weapons Testing [8]

Infrared imaging has long been used in the testing of new weapon systems. A new high-resolution infrared system now offers weapons testers the ability to find performance deficiencies sooner.

When the invitation for bid went out in 1990, the U.S. Department of Defense (DoD) was anxious to fill a projected need for sophisticated thermal imaging systems that would allow in-depth weapon testing and evaluation at night and in poor visibility. DoD officials realized that testing at night would protect the classified nature of new weapon technology and maximize the efficient use and productivity of existing weapon ranges, the latter of which has become particularly important in the wake of Congressionally-mandated defense cuts and planned range closures. The DoD further determined that high-resolution infrared (IR) imaging systems would help spur the development of new weapons designed to operate without visible illumination in fog, haze, smog and battlefield smoke.

IR cameras have evolved from bulky, multiple component systems often called mechanical scanning systems to simple-to-use, staring focal plane array-based systems under microprocessor control. While IR cameras have played an important role in night testing for some time, inadequate dimensional accuracy and spatial resolution have limited their use primarily to target acquisition and tracking. Smog, dust, smoke, and fog are some of the conditions that pose problems for ranges that rely exclusively on near-infrared (NIR) or visible cameras.

With the delivery in 1995 of the last three metric infrared imaging cameras (MIRIC) manufactured by Amber, a Raytheon Company (Goleta, Calif.), the Naval Air Warfare Center Weapons Division (NAW-CWD) in China Lake, California is able to conduct tests that were previously impossible to perform. The use of high-speed high-resolution IR cameras in several metric infrared imaging systems (MIRIS) developed by the NAW-CWD promises to increase the effective test time on our nation's weapon ranges. MIRIS can help determine the attitude of the object under surveillance, as well as the intercept miss distance, and may uncover potential problems early in a weapon's development cycle, a benefit that could amount to substantial cost savings. Moreover, by providing test support in realistic environments, MIRIS may prevent weapon systems with undocumented performance deficiencies from being cleared for manufacture and introduction into active forces.

To satisfactorily perform tasks now being done under ideal conditions by visible systems, MIRIS developers determined their system must reach an angular resolution of 10 microradians—the width of a quarter as viewed from one and a half miles. The focal plane array (FPA) is the critical key to improved performance and is perhaps the most crucial component in these cameras. The 512 x 484 pixel snapshot MIRIS FPA is integrated into a dewar and cold-shield matched to a fixed lens for 100 percent cold-shield efficiency. The accompanying camera lens provides a 15 degree field-of-view (FoV) and can be focused via remote control. The camera's post processor—which outputs MIRIC image information in both analog and digital formats—performs uniformity (offset and gain) correction for neighboring pixels, achieving the effect of a near-perfect FPA.

Exhibit 3.2.2.1-1: Enhanced Weapons Testing Using Infrared Technology

Source: "New Infrared Camera Improves U.S. Navy Weapons Testing," *Defense and Security Electronics*, May 1996

Positive Identification Using Infrared Facial Imagery

Positive identification of an individual is a requirement that is a major part of the classic security, legal, banking, and police systems. Identification can be used to grant or deny access to a secured facility, to give authority to take action or, in police work, to establish the identity of an individual. The single technology that offers accurate and non-intrusive identification is infrared facial recognition technology (IR FRT). Like a thumbprint, each one of us has a unique thermal signature. The IR radiation from relatively low-temperature objects, such as the human body, peaks at about 11 microns, while hotter objects peak at shorter wavelengths. These bands are of interest in military applications specifically because imaging of distant objects is the goal.

Current research in IR FRT is based on the positive attributes of basic IR characteristics combined with a unique human facial identification capability using mathematical algorithms and a computer Since the human face generates its emitted heat based on the individual's vascular system and other physiological characteristics, its elemental shapes, or areas of relative heat radiation, persist over time and are not affected by aging or health. Additionally, the emission pattern, or thermogram, is not affected by light or by moderate ambient temperature variations. As a result of the basic IR characteristics and the computer-based recognition solution, the recognition effort is passive, non-intrusive, light-independent, and invulnerable to disguises.

IR provides a unique image that cannot be counterfeited and is available under any condition with unique advantages such as not being vulnerable to low light levels, cosmetic changes, seasonal changes in background, or physiological alterations. Every individual is uniquely different from other humans to such a degree that even identical twins have slight variations of features and body system structure. The body's core temperature is higher than the heat of the extremities. Consequently, blood is effectively "preheated" and retains a relatively higher temperature as it circulates in the facial area. While metabolic action is taking place in the face and heat is being generated, it is relatively less than the heat being carried throughout the facial vascular system.

The heat in the facial area is constantly dissipating but, because the facial structure is not uniform, the heat dissipation is also not uniform. The thermal appearance of the face is created by a combination of thermal properties related to the underlying vascular structure and the shape and density of bone, subcutaneous tissue, cartilage, skin and so forth, all of which are not uniform. With the large number of properties influencing facial thermal appearance and the extremely large number of variations possible in each of these properties, the certainty of unique facial thermal appearance among individual human beings is virtually 100 percent.

Applications

- Cooperative Access Control Systems (high-value facility protection; would replace badge and reader)
- Non-Cooperative Identification of Small Populations (police, counter-drug, and counter-terrorism)
- Biometric Population Registration (prisoners and military applications)
- Computer and Communications Security (high-value information systems)
- Bank and Credit Card Security Systems

Exhibit 3.2.2.1-2: Individual Identification Using Infrared Technology

Source: "Positive Identification Using Infrared Facial Imagery," *Defense and Security Electronics*, March 1996

Research for IR Application to Bridge Fault Inspection at Northwestern University

Current visual inspection does not provide accurate assessment of bridge condition and is characterized by methods which are slow, qualitative, and potentially hazardous for the inspector. Several possible optical inspection techniques exist, including IR Thermography and Visual Color Imaging, to support and assist future inspections.

Thermography recognizes and measures defects and structural flaws by means of detection and visualization of thermal gradients on the surface of the target. To date this capability has been successful in identifying "signature-specific" types of defects. By leveraging new types of high resolution IR FPAs which have been introduced and implemented in commercially available instrumentation, it is believed that significant improvements can be made for this application of IR technology. Research efforts in this area have been revitalized in order to evaluate and further expand previous attempts to use IR detection for bridge fault inspection to identify faults such as delamination, coatings, and structural integrity of metal and concrete components.

The goal of visual color imaging is to provide improved performance over human inspection. By using color differentiation, detection of subsurface rust areas based on changes in hue of the top coating, accurate measurements of the rusted area can be detected and measured. Field implementation of imaging colorimetry is quickly becoming economically feasible. Color differentiation using this method can also distinguish surface defects including rust spots, blistering, and delaminations.

Both methods, thermographic analysis and visual color imaging, are non-contact, non-invasive, and can provide real-time inspection results in pictorial format. Ease of transmission in the field is based on the proven experience of the medical community where routinely radiological images are electronically transmitted for remote evaluation. For a defect-free homogeneous material, the "wavefront" of heat passes through the target material uniformly and the detected image is contrast-consistent. Otherwise, the image will appear to have contour lines which indicate potential problems with the bridge structural materials. The Basic Industrial Research Laboratory at Northwestern University has successfully used this technique to detect loose bolts in bolted connection plates as well as the delaminations in the bridge coating system

Exhibit 3.2.2.1-3: Bridge Fault Inspection Using Infrared Technology

Source: Gary Shubinsky, Northwestern University Basic Industrial Research Laboratory

Quantum-Well Infrared Photodetectors Enhance Infrared Capabilities

Raytheon/Amber and NASA Jet Propulsion Laboratory are teamed to develop a revolutionary new infrared (IR) camera with product applications in fields ranging from medicine to environmental protection. Infrared imaging uses differences in heat to "see" objects. The new camera uses highly sensitive quantum-well infrared photodetectors (QWIPS) which are arrays of infrared detectors which cover longer wavelengths than are possible with earlier detectors. The higher sensitivity of long wavelength QWIPS will allow doctors to detect tumors using thermographic analysis; enable pilots to make better landings with improved night vision; assist environmental scientists in monitoring pollution and weather patterns; or help defense forces in the field identify various types of rockets by their plumes. The camera also has potential applications in law enforcement, search and rescue operations, and industrial process control.

Exhibit 3.2.2.1-4: Other Applications Using Infrared Technology

Source: Raytheon/Amber Internet Home Page, *Infrared Products and Markets*

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CHAPTER 4. STRATEGIC MANAGEMENT

4. STRATEGY FOR FUTURE GROWTH

This chapter represents an abstraction of the multi-product adoption model strategy developed for technology-driven decisions, with concepts extended to account for longer term strategic management decisions for large companies with responsibility to masses of stakeholders. Sustainable growth and profitability are two fundamental objectives of strategic management for most businesses which have in large part contributed to the development of the multi-product adoption model described in Chapter 3. The intention of this discussion is to identify a linkage between short and long term goals using the multi-product adoption model.

4.1 Balancing Profitability and Market Share with Socio-Economic Responsibility

As the United States transitions to higher degrees of manufacturing automation in the global marketplace, competitive edge will only be sustainable through rapid responses to changes in customer needs and unclouded vision into future customer values. Many economists suggest that the United States has entered a new evolutionary phase of economic development, growing from an agriculture-based economy to one of manufacturing, and finally to a service-based economy. Often the service-based economy is referred to as "the post-industrial economy" [13]. In accord with this school of thought is the relative decline of manufacturing employment in the U.S., from 50 percent of all jobs in 1950 to 20 percent now.

At several points in this thesis the concept of portable skill sets has been mentioned. The optimal balance of profitability and market share with socio-economic responsibility is obviously highly dependent on the specific nature of the company, its culture, and the neighboring environment, but one aspect of this challenge is clear—the next generation of employees will require higher breadth of more specialized skills. Whether these skills are manufacturing-oriented or service-oriented, the source of such a highly skilled work force resides in the ability of local educational systems to prepare future generations for the dynamic business environment of such an economy. In order for the United States economy to continue to grow at the precedent rate set by manufacturing competence, industry and academics must create a societal structure which supports continued achievement toward higher-level transferable skill sets.

The U.S. must respond to the evolutionary changes in the global business environment with greater alignment of industrial needs and academic offerings. Emphasis of government-industry-university partnerships is perhaps the beginning of a new era of revolutionary change in the United States educational infrastructure. Companies should encourage and motivate, if not force, employees to establish and maintain transferable skill sets which are modular and flexible so they can be shifted rapidly as the company's direction changes. Union negotiations should include streamlining of job descriptions, requiring the labor force to be more modular, flexible, and dynamic, so that the same people can and *are willing* to do different jobs. Salaried professionals should be encouraged not only to further their education in job-related classes, but also to other disciplines (within reason). These cultural changes can only be realized through innovative incentive programs. By instituting a policy of continuous improvement of the work force, industry not only provides an incentive structure to support a strategy of growth through innovation, but also achieves an evolutionary consistency between the production strategy and cultural norms of the company.

4.2 Expansion through Acquisition and Internal Growth

There are two fundamental ways to strategically expand a business—acquisition of firms with complementary core competencies, and internal growth based on either growing markets or product diversification. Both approaches seem to be effective when applied with some level of insight and business savvy. Acquisition of companies is a often a simple and effective means to combine businesses for increases in revenue and consolidation of operations.

One aspect of internal growth which is often overlooked is the fact that there are subtle, sometimes hidden, benefits achievable which can be surfaced depending on the business growth strategy. In the scientific community, professionals are naturally motivated by technical challenges and innovative applications of knowledge, education, and previous experience to new and exciting products or services. In addition to the practical strategic implications of sustainable advantage through dual-use technologies, the multi-product adoption model attempts to stimulate the creative side of system design engineers and managers. By continuously offering new products and diverse working situations to employees, the model implicitly addresses an underlying issue of employee morale through targeting the motivating forces of a professional employee base with non-financial incentives and "reputational currency."

4.3 Attaining Multi-Industry Competitive Advantage

By applying the basic tenets of the multi-product adoption model, advantages can be achieved across multiple industries through the innovative adoption of core enabling dual-use technologies. The relative success of the multi-product adoption model depends heavily on the specific implementation and the ability for decision makers to recognize the significance of subtle aspects of multi-industry penetration including the benefits of incremental growth in customer type.

Beyond basic product diversification, the multi-product adoption model attempts to stimulate market growth, accelerate concept-to-prototype cycle time, and leverage explosive advancement in the global information infrastructure to gain competitive advantage through innovative vertical partnering. In every industry-forced market expansion, there will exist some level of uncertainty. The multi-product adoption strategy attempts to exploit the notion that success is not a purely random process, but can be characterized by eliciting intrinsic order from perceived chaos.

> *We cannot expect simply to maximize success, or even to maximize the number of opportunities for achieving success; the only thing we can even partially control in the probability of achieving success resides in maximizing our ability to recognize opportunities as they arise, to possess the education and experience necessary to capitalize on these opportunities, and to identify and mitigate the risks in pursuing them.*
>
> Bob McCarthy
> MIT System Design and Management Program
> Senior Engineer, Raytheon Electronic Systems

BIBLIOGRAPHY AND REFERENCES

[1] Ancona, D., T. Kochan, J. Van Maanen, M. Scully, D. Eleanor Westney, Managing for the Future, Massachusetts Institute of Technology, 1995.

[2] Auerbach, J., "Raytheon Beefs up on Defense," *The Boston Globe*, 9 April 1996.

[3] Ayoob, M., "Aerospace Defense Contracting in the 1990s—Industry and Strategy Analysis," *Babson College MBA Program Independent Research*, August 1995.

[4] Balas, G., J. Doyle, K. Glover, A. Packard, and R. Smith, μ-Analysis and Synthesis Toolbox User's Guide, MUSYN and The Math Works Inc., 1990-1993.

[5] Barton, D., "Radar Systems and Technology," Raytheon Company, Lectures 1-10.

[6] Boothroyd, G, and P. Dewhurst, Product Design for Assembly, Boothroyd Dewhurst, Inc., Wakefield, RI, 1989.

[7] Boothroyd, G, and P. Dewhurst, Product Design, Manufacturing, and Assembly, Boothroyd Dewhurst, Inc., Wakefield, RI, 1994.

[8] Caffee, L. and P. Keller, "New Infrared Camera Improves U.S. Navy Weapons Testing," *Defense & Security Electronics*, May 1996.

[9] Carr, D.K. and H.J. Johnson, Best Practices in Reengineering: What Works and What Doesn't in the Reengineering Process, McGraw Hill, Inc. New York, NY, 1995.

[10] Chang, C., N. Fekete, A. Amstutz, and J.D. Powell, "Air-Fuel Ratio Control in Spark-Ignition Engines Using Estimation Theory," *IEEE Transactions on Control Systems Technology*, Volume 3, Number 1, March 1995.

[11] Clausing, D. and S. Pugh, "Enhanced Quality Function Deployment," *Design and Productivity Conference*, Honolulu, Hawaii, February 6-8, 1991.

[12] Clausing, D., L. Cohen, and M. Phadke, "Systems Engineering: A Competitive Advantage in the Commercial Market," Tutorial viewgraphs, *INCOSE Annual International Symposium*, Boston, Massachusetts, July 7-11, 1996.

[13] Cohen, S. and J. Zysman, "The Myth of a Post Industrial Economy," *Technology Review*, February-March 1987.

[14] Davidson, W.H., "Beyond Reengineering: The Three Phases of Business Transformation," IBM Systems Journal, Vol. 32, No. 1, January 1993 (reprinted in IEEE Engineering Management Review, Vol.23, No. 2, Summer 1996).

[15] Dean, E.B. and R. Unal, "Designing for Cost," *Transactions of the American Association of Cost Engineers*, 35th Annual Meeting, June 23-26, 1991.

[16] Dean, E.B. and R. Unal, "Elements for Designing for Cost," presented at *AIAA 1992 Aerospace Design Conference*, 35th Annual Meeting, June 23-26, 1991.

[17] Deming, W.E., Out of the Crisis, Massachusetts Institute of Technology Center for Advanced Engineering Study, Cambridge, MA, 1986.

[18] Dorr, R., "Mergers (Again!), Missiles, and More," *Aerospace America*, March 1996.

[19] Douglas, J. and M. Athans, "Robust Linear Quadratic Design with Real Parameter Uncertainty," *IEEE Trans. Automat. Contr.*, vol. 39, pp.107-111, January 1994.

[20] Doyle, J., A. Packard, Kemin Zhou, "Review of LFTs, LMIs, and μ," *IEEE Proc. of the 30th Conference on Decision and Control*, pp.1227-1232, December 1991.

[21] Doyle, J., B. Francis, and A. Tannenbaum, Feedback Control Theory, Macmillan Publishing Company, 1982.

[22] Doyle, J., K. Glover, P. Khargonekar, and B. Francis, " State-Space Solutions to Standard H_2 and H-Infinity Control Problems," *IEEE Trans. Automat. Contr.*, vol. 34, pp.831-847, August 1989.

[23] Duffie, N. and V. Prabhu, "Distributed System-Level Control of Vehicles in a High Performance Materials Transfer System," *IEEE Transactions on Control Systems Technology*, Volume 3, Number 2, June 1995.

[24] Edeburn. M., "A Case Study of Two Autopilot Design Methodologies: Linear Quadratic and H-Infinity for a Tail-Controlled Missile," *Master's Thesis, Massachusetts Institute of Technology*, May 1993.

[25] Eppinger, S., "Identifying Controlling Features of Engineering Design Iteration," *MIT Sloan School of Management Working Paper*, Revised July 1995.

[26] Eppinger, S., D. Whitney, R. Smith, and D. Gebala, "A Model-Based Method for Organizing Tasks in Product Development," *Research in Engineering Design*, Massachusetts Institute of Technology, 1994.

[27] Etkin, B., Dynamics of Flight: Stability and Control, John Wiley and Sons, Inc., 1982.

[28] Evans, D., "Positive Identification Using Infrared Facial Imagery," *Defense & Security Electronics*, March 1996.

[29] Everett Leader Herald News Gazette, "Senator Kerry, MIT Officials Join Mayors on TeleCom℠ City," 1 August 1996.

[30] Grady, J., System Integration, CRC Press, 1994.

[31] Grady, J., System Requirements Analysis, McGraw-Hill, Inc., 1993.

[32] Hall, M.N., "Reducing Long Term System Cost by Expanding the Role of the Systems Engineer," *Proceedings of the International Symposium on Technology and Society*, IEEE, Washington DC, 23 October 1993.

[33] Hammer, M. and J. Champy, Re-Engineering the Corporation: A Manifesto for Business Revolution, Harper Business, 1993.

[34] Hauser, J. and D. Clausing, "The House of Quality," *Harvard Business Review*, May-June 1988.

[35] Hogan, B., "MISSILES, Last Line of Defense," *Design News*, 24 April 1995.

[36] Institute for Systems Research—University of Maryland, "Virtual Factories for Electro-Mechanical Device Manufacturing," *NASA Tech Briefs*, Vol. 20, No. 7, July 1996.

[37] Japanese Technology Evaluation Center, "Electronic Manufacturing and Packaging in Japan," *JTEC Report Executive Summary*, 1995.

[38] JTEC, "JTEC Panel on Electronic Manufacturing and Packaging Study Report," 1995.

[39] JTEC, "JTEC Panel on Optoelectronics Study Report," 1996.

[40] Kaminski, P., "Enabling Technologies for the 21st Century," *Statement of the Undersecretary of Defense for Acquisition and Technology Before the House Permanent Select Committee on Intelligence*, 18 October 1995.

[41] Kaminski, P., "Reducing Life Cycle Costs for New and Fielded Systems," *Memorandum for Distribution*, The Office of the Under Secretary of Defense, 1996.

[42] Kaminski, P., "Sustaining Flight Through the Power of Knowledge," *Ira C. Eaker Distinguished Lecture on National Defense Policy*, 3 May 1996.

[43] Kerzner, H., Project Management: A Systems Approach to Planning, Scheduling, and Controlling, Van Nostrand Reinhold, 1995.

[44] Kramer, F. and A. Calise, "Fixed Order Dynamic Compensation for Linear Multivariable Systems," *AIAA Journal of Guidance, Control, and Dynamics*, February 1987.

[45] Krasner, J. and M. Kneil, "Raytheon's Perfectionists May Rocket Out of State," *The Boston Herald*, 2 May 1995.

[46] Krikorian, G., "Business with Defense Department Means Integrated Decision Making," *National Defense*, March 1996.

[47] Krikorian, G., "Defense Acquisition Breakthrough Reached Via Re-Engineered Rules," *National Defense*, February 1996.

[48] Lalli, F., "Why Should You Invest in Companies that Invest in their Workers," *Money*, March 1996.

[49] Larrere, J. and D. Williams, "Helping Workers Grow with Firms," *The Boston Globe*, 25 June 1996.

[50] Leonard-Barton, D., "Core Capabilities and Core Rigidities: A Paradox in Managing New Product Development," *Strategic Management Journal*, Vol. 13, 1992.

[51] Maciejowski, J.M., Multivariable Feedback Design, Addison-Wesley Publishing Company, 1989.

[52] Magnanti, T., MIT 15.059 Lecture Notes, Sprint Term, 1996.

[53] Malden Redevelopment Authority, *TeleCom℠ City—A New Vision For a New Age*, 1996.

[54] Manganelli, R.L. and M.M. Klein, The Reengineering Handbook: A Step-by-Step Guide to Business Transformation, AMACON, New York, NY, 1994.

[55] McCarthy, R.J. and J. Lewitzky, "SM-2 Aegis Block IVA Multivariable Midcourse/Terminal Autopilot Concept Definition, Final Report," Raytheon Electronic Systems, August 1995.

[56] McCarthy, R.J., "QuadAero Intelligent Autonomous Unmanned Aerial Vehicle Flight Control System Design, Development, and Implementation," *Master's Project - Georgia Tech MSEE*, August 1993.

[57] McCarthy, R.J., "Multivariable Autopilot Concept Trade Study Analysis, Linear Quadratic versus H-Infinity/Mu-Synthesis," HRMCS ATD presentation viewgraphs, Raytheon Electronic Systems, July 1996.

[58] McCord, K, and S. Eppinger, "Managing the Integration Problem in Concurrent Engineering," *MIT Sloan School of Management Working Paper*, Revised August 1993.

[59] Mintz, J. (Washington Post), "Boeing to Buy Units of Rockwell: $3.2b Deal Cut for Space and Defense Divisions," *The Boston Globe*, 2 August 1996.

[60] Motorola, "Motorola's Six Sigma Quality Process," presentation viewgraphs, 1988.

[61] Nahmias, S., Production and Operation Analysis, Richard D. Irwin, Inc., 1993.

[62] Nesline, F.W., B. Wells, and P.Zarchan, "A combined Optimal/Classical Approach to Robust Missile Autopilot Design," *AIAA Guidance and Control Conference*, Boulder, CO, 1979.

[63] Office of the Deputy Under Secretary of Defense (Acquisition Reform), "Cost As An Independent Variable," *Presentation Viewgraphs*, 1996.

[64] O'Brien, R., P. Iglesias, and T. Urban, "Vehicle Lateral Control for Automated Highway System," *IEEE Transactions on Control Systems Technology*, Vol.4, No.3, May 1996.

[65] Oster, S., Modern Competitive Analysis, Oxford University Press, 1994.

[66] Packard, A., J. Doyle, G. Balas, "Linear, Multivariable Robust Control with a μ Perspective," *Trans. of the ASME*, Vol.115, pp.426-438, June 1993.

[67] Perry, W., "Report to the President and Congress from the Secretary of Defense," February 1995.

[68] Phadke, M.S., Quality Engineering Using Robust Design, Prentice Hall, Englewood Cliffs NJ, 1989.

[69] Porter, M., Competitive Advantage of Nations, The Free Press, NY, 1990.

[70] Prahalad C. and G. Hamel, "The Core Competence of the Corporation," *Harvard Business Review*, Number 90-3, May-June 1990.

[71] Raytheon Company, *1993, 1994, and 1995 Annual Reports.*

[72] Raytheon Company, "Amber and NASA Jet Propulsion Lab Develop New IR Camera," *Raytheon News*, Raytheon Company, April 1996.

[73] Raytheon Company, "Final Report for The Vertical Partnering Subcontractor Facilitization," CDRL No. A001, ManTech Department of the Air Force, September 1995.

[74] Raytheon Company, "JED Ranks Raytheon as World's Top EW Company for 1995," *Raytheon News*, Raytheon Company, May 1996.

[75] Raytheon Company, "Raytheon Among Top Exporters," *Raytheon News*, Raytheon Company, February 1996.

[76] Raytheon Company, "Raytheon and Brazil Sign Historic $1.3B SIVAM Contract," *Raytheon News*, Raytheon Company, June 1995.

[77] Raytheon Company, "Raytheon Electronic Systems New Hire Orientation," September 1995.

[78] Raytheon Company, "The Massachusetts Economic Situation," presentation viewgraphs, 1995.

[79] Raytheon Electronic Systems, "Affordable Multi-Missile Manufacturing Program (AM^3) Post Award Briefing and Program Kickoff Meeting for IMT and IPT," 28-29 September 1995.

[80] Raytheon Electronic Systems, "National Airport On-Line with Terminal Doppler," *RES News*, Raytheon Electronic Systems, May 1996.

[81] Rechtin, E., Systems Architecting: Creating and Building Complex Systems, Prentice Hall, Englewood Cliffs, NJ, 1991.

[82] Reichert, R., "Application of H-Infinity to Missile Autopilot Design," *AIAA Journal of Guidance, Control and Dynamics*, pp.1065-1072, October 1992.

[83] Reichert, R., "Dynamic Scheduling of Modern-Robust-Control Autopilot Designs for Missiles," *IEEE Control Systems*, pp.35-42, October 1992.

[84] Reiner, J., G. Balas, and W. Garrard, "Robust Dynamic Inversion for Control of Highly Maneuverable Aircraft," *AIAA Journal of Guidance, Control and Dynamics*, vol.18, pp.18-24, January-February 1995.

[85] Rishi, P., "Assessing the Software Development Process in Providing Customer Value," *MIT Master's Thesis*, August 1996.

[86] Ropelewski, R., "Partnership: The Price of Entry," *Aerospace America*, June 1996.

[87] Roskam, J., Airplane Design, Parts I-VIII, Design, Analysis and Research Corp., 1990.

[88] Seaman, C.M., A.A. Desrochers, and G.F. List, "Multi-objective Optimization of a Plastic Injection Molding Process," *IEEE Transactions on Control Systems Technology*, Volume 2, Number 3, September 1994.

[89] Shamma, J. and M. Athans, "Analysis of Gain Scheduled Control for Nonlinear Plants," *IEEE Trans. Automat. Contr.*, vol. 35, pp.898-907, August 1990.

[90] Storm, W., "Detailed Design of a Multiobject Inertial Frame Tracker," Raytheon Company working paper, 1995.

[91] Temple, S., "Laboratories Continue Winning Technology Tradition in '95," *PES News*, Raytheon Electronic Systems, May 1996.

[92] Texas Instruments / Hughes AM3 Team, "AM3 Phase 1 Preliminary Findings on the Factors Influencing Missile Costs," presentation viewgraphs, 18 November 1995.

[93] Texas Instruments / Hughes AM3 Team, "ARPA'a Affordable Multi-Missile Manufacturing Program (AM3), Integrating People, Products, and Processes," presentation slides, 1995.

[94] Thurow, L., "N.E. Business Sense: Before Giving Away the State, Remember Region's Strengths," *The Boston Globe*, 16 July 1996.

[95] U.S. Department of Defense, <u>Parametric Cost Estimating Handbook</u>, Joint Government/Industry Parametric Cost Estimating Initiative Steering Committee, Fall 1995.

[96] U.S. Navy, "Methods and Metrics for Product Success, A Dual-Use Guide," Office of the Assistant of the Navy (RD&A) Product Integrity Directorate, July 1994.

[97] Ulrich, K. and S. Eppinger, <u>Product Design and Development</u>, McGraw-Hill, Inc., 1995.

[98] Vartebedian, R., "Defense Firms Set to Win IRS Battle," *The Boston Globe*, 25 June 1996.

[99] Viswanathan, K., S. Eppinger, and D. Whitney, "A Model-Based Framework to Overlap Product Development Activities," *MIT Sloan School of Management Working Paper*, Revised September 1995.

[100] Warsh, D., "The Raytheon Case: When Good People Face Hard Choices," The Boston Globe, 5 March 1995.

[101] Warsh, D., "What Does E-Systems Mean for Raytheon," *The Boston Globe*, 9 May 1995.

[102] Weaver, J., "Life-Cycle Cost Reductions at Get-Go Yield Savings for Military and Industry," *National Defense*, March 1996.

[103] Williams, J.E. and R.J. Krieger, "Accuracy Criteria for Evaluating Supersonic Aerodynamic Coefficient Predictions," McDonnell Douglas Astronautics Company.

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APPENDIX 1. GOVERNMENT INITIATIVES

A.1 Initiatives to Achieve Higher Cost-Effectiveness for Government Procurement

This section focuses on describing two initiatives under the direction of the Advanced Research Projects Agency (ARPA) of the United States Department of Defense—the Affordable Multi-Missile Manufacturing (AM^3) Program and the Technology Re-Investment Project (TRP). These particular programs are intended to serve as illustrative examples of a much larger scale evolutionary movement toward the development of dual-use technologies and successful technology transfer across military and commercial high-technology products. Therefore, the emphasis of this section is to present an introduction to fundamental mission of these programs, not to provide a comprehensive description of each program.

A.1.1 Affordable Multi-Missile Manufacturing Program

The Affordable Multi-Missile Manufacturing (AM^3) Program is an Advanced Technology Demonstration (ATD) sponsored by the Advanced Research Projects Agency (ARPA). The objective of the AM^3 Program is to demonstrate advanced missile design and manufacturing concepts for the future incorporation of systems which can substantially reduce the cost of the United States Department of Defense (DoD) procurement and research for advanced technology defense systems. In contrast with many performance-oriented ATDs, the goal of this effort is to treat cost as the performance index and leverage increased commonality of components across products to achieve greater economies of scale and optimize resource utilization. Critical elements of the AM^3 initiative include flexible manufacturing, lean production practices, six sigma quality initiatives, and statistical process control to simultaneously achieve reductions in development cost and accelerated product development through rapid insertion of new technology.

The AM^3 Program is a collective government-industry effort to establish prototype best system design practices from a perspective of cost-efficiency and producibility. The focus of the AM^3 effort is on missile seekers and guidance and control sections which account for more than 60 percent of typical missile unit production costs. Stemming from a model of flexible manufacturing, platform-based design, and in-line sequencing developed by the automotive and commercial aircraft industries, the **missile enterprise of the future** will no longer be dedicated to a single product line. In order to remain competitive in the world of rapidly changing demands for enabling technologies and military system capabilities, missile production lines must become agile and modular using automated manufacturing capabilities and platform-based design practices to achieve an ability to respond quickly to unforeseen changes in customer needs due to changes in threat characteristics. The DoD is revisiting it's strategies and assessing existing capacity and inventory, attempting to optimize across the armed forces to achieve the most cost-effective product balance for meeting the needs of maintained U.S. national security.

Exhibit A.1.1-1 depicts a vision of the future missile manufacturing enterprise. This particular concept was developed by the Texas Instruments/Hughes AM^3 Program Team but is generally representative of the collective objectives of the entire Government-Industry Consortium.

Exhibit A.1.1-1: A Vision for the Missile Manufacturing Enterprise of the Future [92,93]

"As Is" Enterprise	"To Be" Enterprise
• Single Product Lines • Process Errors • Limited Automation • Performance Driven Design • Dedicated Tool Set • Military Acquisition Systems • Adversarial Relations with Customer/Suppliers • Data not Widely Shared • Stovepipe Environment • Long Costly Development Cycles (obsolete designs before release) • Old Technology Fielded • Depots	• Multi-Use Production Lines • Automated Process Controls and Assembly • Commercial-Like Products • Six Sigma Quality • Affordability Driven Design • Use of Commercial Acquisition and Management Systems • Fully Networked Enterprise (customer/suppliers) • Shared Data Bases • Simulation and Prototyping to Reduce Risk • Empowered Teams • Factory Integrated Repair • Common Design, Tooling, Test Equipment

Source: Texas Instruments/Hughes AM3 Team Presentation, 1995

A fundamental element of the AM^3 Program is to determine the optimal balance between cost, time, and performance—to deliver high quality missile systems which meet performance requirements at an affordable price, developed and produced with accelerated development schedules, but are not over-designed with non-value added features. One key to achieving this goal is a philosophy of rapid iterative design cycles which explore alternative design options early when the cost-impact of decisions is most critical. Selection of technologies and components should be through knowledge-based engagement using design processes which are dependable, reliable, and repeatable.

The "missile factory of the future" vision provides a close linkage between the factory and the user-environment—the battlefield. Emphasis is placed on life cycle cost of ownership and ease of downstream upgrading with new technologies for future growth. The AM^3 concept requires agile vertical integration of people, processes, and products engaged in trust-based relationships providing world-class technology and service to every customer. Much as the automotive industry has made efforts to design products by matching technology with "the voice of the customer," the missile manufacturing business under the AM^3 Program philosophy will better meet the needs of the customer and will perform better under market-driven industry economics.

A focus of strategic vertical partnering for high value common missile components such as inertial instrument suites, gimbals, global positioning systems, optics, antennas, etc., will ensure a best value design with manufacturing flexibility for multiple system insertion. The AM^3 Program incorporates proven best practices from the defense and commercial product development methodologies, with appropriate metrics to measure continuous improvements in performance and efficiency. Gains in efficiency focus on characterizing existing products and processes—identifying form, fit, and function—which can be exploited to achieve commonality among components. By developing key enabling technologies which are modular and scalable, the factory of the future will achieve efficiency based on economies of scale from common production lines and platform-based manufacturing design practices which are lean, agile, modular, and flexible.

A.1.2 Technology Reinvestment Project

The Technology Reinvestment Project (TRP), sponsored by ARPA, is a unique virtual organization which spreads across many agencies and offices in the United States government. Participating member enterprises include all of the ARPA Technical Offices; the Military Services; the Departments of Commerce, Energy and Transportation; the National Aeronautics and Space Administration (NASA); and the National Science Foundation. The central mission of the TRP is to stimulate a merging of defense and commercial industrial bases to assure Department of Defense access to critical defense-related technologies at a cost kept low through simultaneous commercial interest.

Technology reinvestment emphasizes dual-use innovation for a stronger defense at an affordable cost. Under the management and sponsorship of ARPA, the Technology Reinvestment Project ensures that technology development vital to current and future national security is maintained and supported by innovative policies to leverage the strengths of a powerful commercial business base in the United States. TRP addresses all significant aspects of defining innovative strategies for developing future enabling technologies including optimized military mobility and deployment; command, control, communications, computers, and intelligence (C^4I); battlefield sensors, casualty treatment; electronics design and manufacturing; mechanical systems and materials; and weapons and survivability.

As the strategy of the DoD responds to meet a diverse range of threats in today's economically challenged business environment, what remains constant is the value of the U.S. commercial industrial base and the technology capability for national security. The ARPA TRP initiative is an unconventional strategy which benefits both large and small businesses by encouragement of unilateral leverage of strengths to provide two-way technology transfer and increased economies of scale. TRP has its own contracting authority outside the Federal Acquisition Regulations. Thus, contract negotiations are typically accomplished in a more efficient and streamlined manner. Since this approach encourages business from an established powerful commercial sector, maintained military superiority will be sustained by overcoming the technological challenges posed by uncertain threats, fiscal constraints, and revolutionary changes in the nature of modem battle. Combining the strengths of existing defense technology companies and high-tech commercial enterprises will lead to technology development characterized by greater affordability, availability, and continuous improvement. One key aspect of this strategy is to deliberately increase the amount of dual-use research.

The TRP initiative has already begun shaping the technology development for a new era marked by cost sharing, integrated product design teams, innovative agreements, and competitive selection based on merit. TRP management is organized to be lean and effective with temporary use of federal assets for startup without the inertia of large permanent bureaucracy. Once individual projects are selected they are assigned to the agency best suited to manage them. Typical projects last two years with the potential to yield commercial products shortly after the end of TRP funding. Two main approaches comprise the core of the TRP—leveraging of existing commercial technologies into defense systems and products, and embedding new and existing defense technologies into commercial product applications. Refer to Exhibit A.1.2-1 for a set of selected examples of TRP individual project examples.

Exhibit A.1.2-1: Selected Examples of Technology Reinvestment Program (TRP) Projects

- Advanced Automatic Train Control System
- Advanced Picture Archiving and Communications System (PACS)
- Asynchronous Transfer Mode Interoperability Testbed for the National Information Infrastructure
- Automotive Collision Avoidance System
- Autonomous Landing Guidance
- Developing Speech Recognition for Future Digital Signal Processing in Handheld Computers
- Development and Application of Advanced Dual-Use Microwave Technologies for Wireless Communication and Sensors for Intelligent Vehicle Highway System Vehicles
- Digital X-Ray System and Battlefield Applications
- TI/Raytheon "Leap-Ahead" Approach to U.S. Flat Panel Display Competitiveness

Source: TRP Internet Home Page

A.1.3 Methods and Metrics—A Roadmap to Reduced Life Cycle Cost

Risk management is a general term referring to a set of processes which can be implemented to address several distinct risk elements including technical, financial, production, schedule, and marketing, goals. This section addresses one specific area of risk management for successful product development—technical risk management. Technical risk includes elements of a project which can be effectively monitored and controlled with measurements of effectiveness (MOEs) throughout a product development cycle. Technical risk ties back to system architecture and the decisions made early in the design process. The significance of these early decisions is high because they directly impact a downstream ability to manufacture, assemble, operate, and support a particular product. This section addresses the risk items which can be continuously tracked using structured methods and quantifiable metrics to balance performance objectives with cost and producibility constraints.

In the defense system development and procurement process, current acquisition efforts rely on Military Specifications and Standards, coupled with a cumbersome level of adversarial oversight practices intended to assure compliance in order to achieve product success. This inefficient means of doing business persists due the U.S. Government's belief that reliance on specifications and standards reduces risk and because industry believes that these standards helps maintain a constant and level competitive playing field [96]. Fortunately, the acquisition reform process is beginning to change some of these behavioral and cultural dynamics to allow for greater freedom in gaining cost efficiencies from proven best practices and leverage from a strong national commercial business base in the United States.

Because the world has changed so drastically over the past decade, the reductions in defense spending have forced a re-visitation of business practices in developing the future high technology products which stem from defense system research and development. As a result, it is widely recognized that the strides made in the commercial sector have resulted in accepted best practices and quality standards. The U.S. Government is becoming increasingly willing to share some of the inherent development risk associated with new products and processes. Industry is responding to this new challenge by striving to understand customer needs through integrated product and process design teams which invite the customer to become an active participant in the design process, rather than a distant skeptical spectator.

Companies must develop products which meet technical performance specifications, but avoid providing additional benefits which add little or no real value, and deliver high quality products which operate correctly the first time they are used. The development and production of these high technology products must be on-schedule and on-budget, with mechanisms in place for assuring continuous improvements in production efficiency throughout the development process and entire life cycle for high-tech products.

A significant component of acquisition reform involves an approach which relies on the use of proven best practices and established MOEs to achieve product success. Acquisition reform must include higher levels of informal interaction among customer, prime contractor, and suppliers in an integrated product design team environment. This approach provides reduced risk to the government while simultaneously allowing industry to compete on product performance and value, not on an ability to manipulate an overly bureaucratic system [96].

Because development of new products and technologies requires exposure to unknown processes, uncertain methods and materials, and outcomes which are variable, the notion of risk introduces the need for risk management which is effective and deliberate. By establishing structured methods and appropriate metrics for assessment and evaluation of program status, continuous improvements can be made throughout the development process. The key to successful product development is in developing a methodology which incorporates a set of metrics which are aligned with the major objectives of the project. Risk is an expected and unavoidable part of any revolutionary growth in product performance or technological innovation. However, knowing the risks and tracking the progress toward mitigating and reducing risk results in seldom interference with successful product development.

A systematic approach to mitigating risk factors through technical risk management includes the basic recognition that risk exists. Handling risks can be accomplished by exhaustively assessing the potential sources of risk in a system. Tracking risk must be a fundamental component of the design and development process. A possible solution is to establish risk assessment milestones and verify over time that risk is decreasing. This approach explicitly forces a visible risk reduction process and reduces the possibility of surprise.

An example model technique which has a natural fit to technical risk management is decision tree analysis. Decision trees can be used to assess the probability of risk and evaluate the magnitude of unwanted outcome due to individual failure modes. Figure A.1.3-1 illustrates a simple decision tree analysis problem setup.

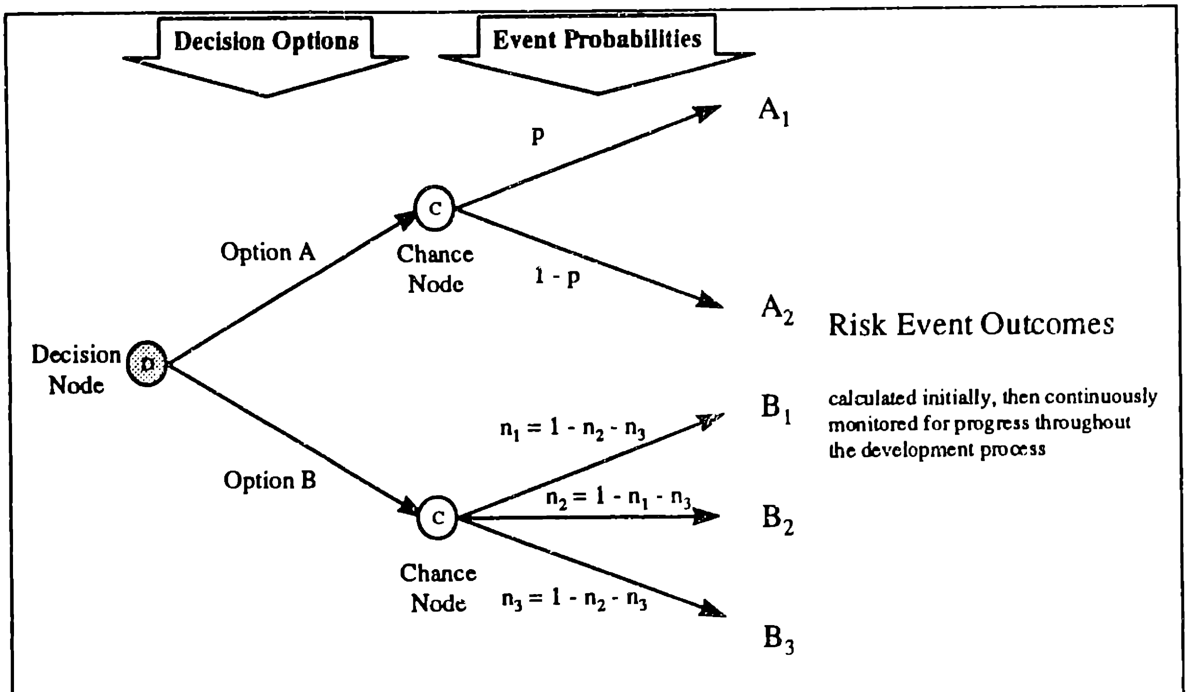

Figure A.1.3-1: Decision Tree Analysis for Technical Risk Assessment

Source: Adapted from Drake and Keeney, *Decision Analysis*, 1978

A structured technical risk management sub-process should be developed and maintained as a part of an overall system engineering effort on each project. A company's perceived ability to manage risk can often be a decision criterion for being awarded government contracts. A system which seems to be effective in constructing a systematic reporting procedure to program management includes formal risk assessment reports tied to milestones and events of an integrated master plan and schedule (IMP/IMS). Spreadsheet models are often useful for risk assessment reporting. Probabilities from the master decision tree and fault failure mode analysis can be tied into a hierarchy of spreadsheet-driven models to maintain continuous monitoring of technical risk with inputs from integrated product team empowered design engineers who are responsible and accountable for these decisions. Other types of risk such as cost and schedule risk can be tied to the technical risk assessment and integrated with a master system engineering plan.

A.1.4 Cost as an Independent Variable

Cost as an Independent Variable (CAIV) is a new programmatic approach being promoted by the Office of the Under Secretary of Defense [41,63]. CAIV is a radical departure from past government procurement practices and previous attempts at lowering unit production cost for defense-related technological products. The key difference from predecessor programs like "design-to-cost" resides in the emerging new acquisition reform environment, where program managers will be empowered and "incentivized" to make design changes based on performance-cost trades during all phases of the program. In principle, CAIV resembles a market-driven pricing strategies which have been successful in the commercial sector for years in such industries as consumer electronics and automobiles.

Significant acquisition reform and streamlining of military standards and specifications provide the necessary support for successful implementation of the CAIV agenda. Specific actions which will catalyze the CAIV process include:

- Stating requirements in terms of system performance and needed military capability without intruding into detailed product design or manufacturing process domains
- Adoption of commercial best practices and the use of commercial parts in military products
- A shift to integrated product team (IPT) management
- Encouragement of common processes.

The objective of CAIV is to provide maximal performance at an affordable cost by setting realistic cost targets in each program phase and optimizing realization of the design space within the bounds of predetermined resources. Life cycle cost reduction is the ultimate goal of CAIV. If customer needs can not be met within cost budgets after exhausting the trade space, then a major milestone decision must be made to either raise the cost targets or cancel the program as unaffordable. Cost goals are used as a program management tool and new contracts will provide tangible incentives for meeting cost targets with performance capability that meets the true warfighter needs. CAIV is the Department of Defense equivalent to best business practices in the commercial sector.

From the perspective of the government or contracting agent, the CAIV strategy entails setting aggressive, realistic cost targets and managing program risks while balancing mission needs with projected resources. In order to provide accurate technical risk identification and assessment, an evaluation must be maintained of exiting production-ready technologies and level of maturation of new technologies required to complete the program within the allocated resources and milestone schedule.

From a prime contractor or subcontractor perspective, the significance of full traceability for costs on existing and previous programs has increased tremendously. In addition to incentives for new contracts which include the CAIV philosophy, future contract award selection criteria will evaluate past performance on an ability to generate accurate and credible cost predictions based on historical process characterization. In short, this means that companies that intend to remain competitive in defense market segments had better establish an infrastructure that reaches beyond basic accounting of aggregate cash flows. With the computer networking resources emerging in the present information age, setting up the infrastructure should be the easy part. Probably the larger challenge is educating the average defense sector product design engineer that predicting costs accurately is actually becoming important.

CAIV Conceptual Approach [63]:

- Setting realistic but aggressive cost objectives early in the acquisition program
- Managing risks to achieve cost, schedule and performance objectives
- Devising appropriate metrics for tracking progress in setting and achieving cost objectives
- Motivating government and industry managers to achieve program objectives
- Putting in place for fielded systems additional incentives to reduce operating and support costs

> *Contrary to common lore, experience has shown that products or systems developed under the CAIV process are, more often than not, the "105% solution" rather than the proverbial "80% solution." CAIV-developed products are generally simpler, easier to build, more reliable, and represent a better match to customer needs than those developed to meet maximum performance specifications. The dramatic-cost reduction potential that accompanies CAIV, especially when coupled with the potential for superior systems and products, makes this a true "win-win" approach for the DoD [63].*
>
> R. Noel Longuemare
> Principal Deputy Under Secretary of Defense,
> Acquisition and Technology

> *This strategy uses the best value approach which requires that we thoroughly scrub program goals, not only for unnecessary mil specs, regulations, and data, but also—and more importantly—for marginal performance improvements that have little to do with actual combat effectiveness, but can drive up cost and schedule through unnecessary program risk. [41].*
>
> Dr. Paul G. Kaminski
> Under Secretary of Defense for Acquisition and Technology

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APPENDIX 2. RAYTHEON COMPANY

A.2 Raytheon Company—Responding to Evolutionary Change in Customer Value

A case study analysis is presented to describe one company's response to the changing technology needs and customer values in the aerospace and electronics industries. Raytheon Company has major defense and commercial operations and competes in multiple markets and industries. An investigation of Raytheon's core competencies, distinctive enabling technologies, and corporate acquisition strategy is fruitful in further describing the state of the aerospace and electronics industries from more of a bottoms-up perspective. This brief analysis introduces Raytheon as a diversified high technology commercial company with a top-tier defense business segment, and concludes with an analysis model for managing organizational change.

A.2.1 Historical Perspective and Analysis of Selected Core Competencies

Raytheon Company is a 71-year old organization with corporate headquarters in Lexington, Massachusetts, and has evolved from a small start-up business committed to the manufacture and design, production and sale of machinery, motors, and their components to an over $12 billion international, high technology enterprise operating in four key business areas: commercial and defense electronics, engineering and construction, aviation, and major appliances.

Today, Raytheon is a diversified high technology enterprise competing in many commercial markets, and is among the five largest defense contractors in the United States. Raytheon employs over 75,000 people worldwide with operations in 47 states throughout the U.S. and has offices in 24 countries around the world. Raytheon's major financial growth periods have unquestionably been fueled by defense system technology research, development, design, production, and support. Diversification efforts have always been a major element in Raytheon's strategy to reduce corporate risk during the cyclic federal spending reductions on defense systems procurement, but it has only been recently that a significant portion of total profits can be attributed to commercial market penetration and revenues from non-defense technology applications.

Arguably, one of Raytheon's main core competencies is the technological development and quality production of radar systems for military and commercial applications. Since the early years of producing radio tubes through a period of unprecedented growth during World War II, Raytheon has been a key contributor to the invention and advancement of microwave and radar technology in the United States. After experiencing some difficult financial times in the 1940s, military orders from the Korean conflict had helped to boost sales by the mid-1950s and Raytheon was once again stable and reasonably profitable.

A series of strategic acquisitions during the 1960s and 1970s was designed to equalize Raytheon's commercial and military earnings with such businesses as major home appliances, textbook publishing, petrochemical construction and exploration, and single- and twin-engine planes (1980). In spite of these diversification efforts, 90 percent of 1987 total earnings still depended on missiles, radar, and communication systems. In 1993, the company reorganized its construction business into Raytheon Engineers and Constructors (RE&C) and merged its appliance business units into a single Appliances Group. The 1990s have once again marked a time of many acquisitions in the quest for stability and maintained corporate growth through strategic diversification.

In 1994, Raytheon won a Brazilian contract worth over $1 billion to build an environmental surveillance and air traffic control system in the Amazon region—the world's largest and most ambitious environmental protection initiative. A team led by Raytheon will develop, produce and install the surveillance system, which is designed to protect the vast Amazon Basin—an area more than half the size of the United States. Raytheon will supply air traffic control radars, automation, flight certification, airborne and ground-based surveillance and environmental sensors, weather radars, telecommunications, specialized software, systems engineering and logistics support, and program management. Once again, the company was able to capitalize on a core competence in advanced sensor technology. This time the scope of the project is larger than any other system like it in existence in the world today. The massive hardware and software systems which are required to support the system for Surveillance of the Amazon (SIVAM) represents a huge achievement for Raytheon's diversification efforts.

> *The mission of the SIVAM project is "... to reduce deforestation, combat illegal mining and drug trafficking, improve health controls, protect indigenous Indian tribes, strengthen border security and communications in rural areas, monitor traffic on inland waterways, and bolster air safety [76].*
>
> James W. Carter, SIVAM Program Manager

The strength of Raytheon's competitive positioning is evident with $790 million in 1995 earnings leading to being ranked the "world's top electronic warfare company" in a February 1996 survey published by the *Journal of Electronic Defense*. In 1995, Raytheon purchased E-Systems, Inc. for $2.3 billion. E-Systems is a maker of advanced electronic and surveillance equipment. Organizationally, E-Systems represents a major contributor to the defense and electronics key business areas for Raytheon, but is a completely separate and unique entity from Raytheon Electronic Systems which is one of the four Raytheon Company divisional business units.

The 1990s mark a period of transition for Raytheon. Under the corporate leadership of chairman Dennis Picard, Raytheon has gained significant ground in moving from a large defense contractor with some commercial business to a multi-industrial commercial company with a strong defense segment. The contribution of defense operations to Raytheon's total profits declined from 67 percent in 1993 to 45 percent in 1994.

In 1995, Raytheon reported net income of $792.5 million, or $3.25 per share, compared with 1994's net income of 596.9 million, or $2.26 per share. Total 1995 sales reached $11.7 billion, the highest in the company's history, compared with sales of $10.0 billion in 1994. Raytheon's total debt came down substantially to $2.7 billion at year-end 1995, compared with a peak of approximately $4 billion earlier in 1995 following the acquisition of E-Systems.

The commercialization strategy orchestrated by Chairman Dennis Picard has taken Raytheon's commercial business groups—Raytheon Engineers and Constructors, Raytheon Aircraft, Raytheon Appliances, and the commercial electronics group—from approximately half of Raytheon's total sales and one-quarter of its earnings in 1991, to nearly 60 percent of total sales and close to half of total earnings in 1995. This shift in business mix occurred as Raytheon's total sales increased from $9.3 billion to $11.7 billion in 1995 and total profits rose from $591.8 million to $792.5 million. Raytheon reported record earnings for first quarter 1996 of $186.5 million, 7.2 percent higher than the year-ago period.

Corporate actions over the past five years under the leadership of Dennis Picard lead have been consistent with an executive strategy to evolve Raytheon into a high technology commercial enterprise with continued growth as a top-tier defense contractor. Figure A.2.1-1 illustrates Raytheon's major business areas based on 1994 sales of $12 billion. Raytheon's competes in four major business areas: commercial and defense electronics, engineering and construction, aviation, and major appliances. To compete effectively cross these areas, Raytheon is organized into six top-level business divisional units discussed in Section A.2.2.

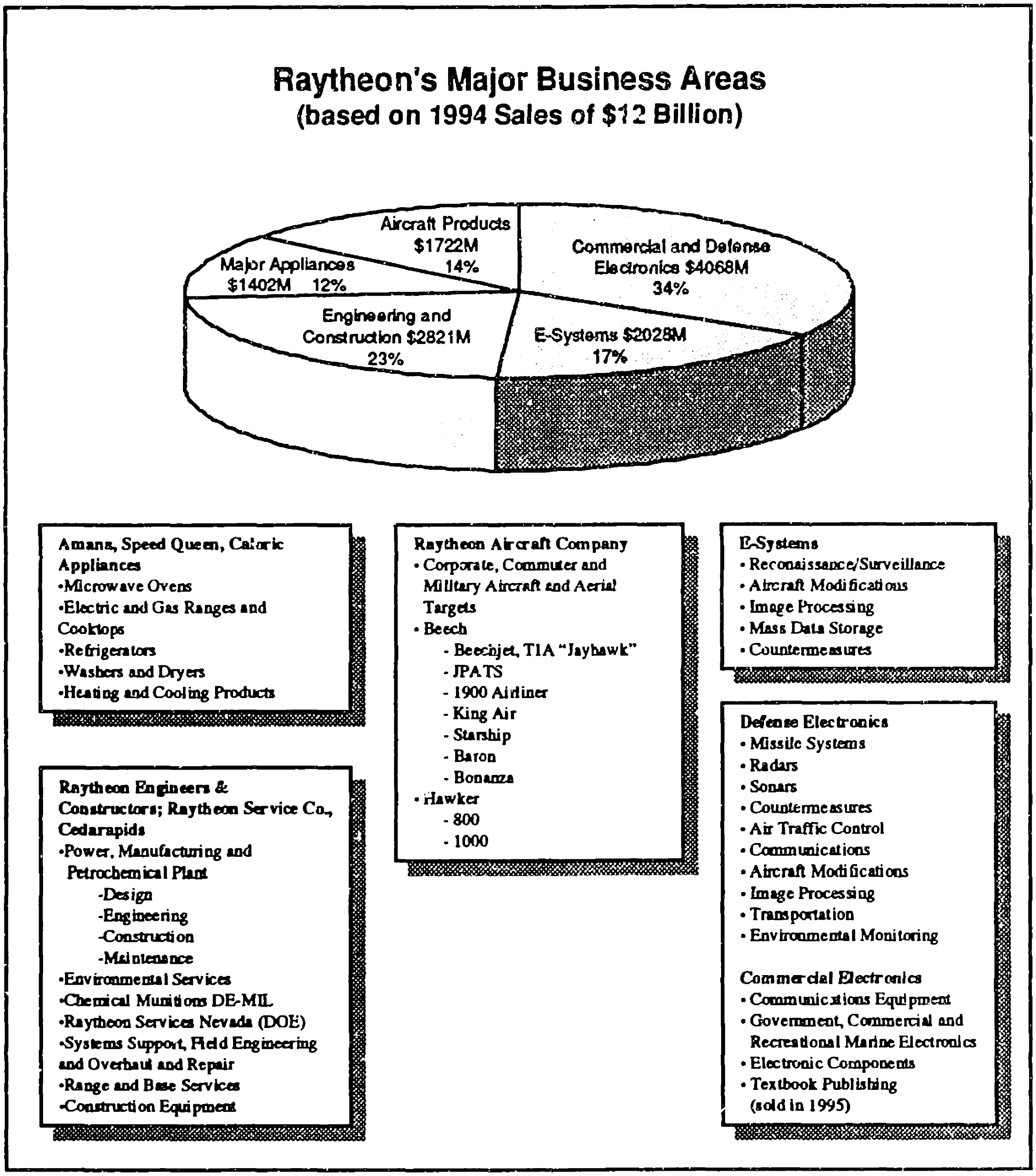

Figure A.2.1-1: Raytheon's Major Business Areas

Source: *Raytheon Company New Hire Orientation Handbook*, 1995

A.2.2 Organizational Structure

Raytheon's top-level organizational structure supports a strategy of producing a diversified portfolio of commercial and defense electronics, leveraging core competencies in defense system technologies to competitive advantage in commercial and defense markets. Exhibit A.2.2-1 illustrates the corporate management structure at Raytheon under the leadership of Chairman Dennis J. Picard. The organization is divided into six divisional business units which compete in the four key business areas previously mentioned—commercial and defense electronics, engineering and construction, aviation, and major appliances. Commercial and defense electronics is subdivided into Raytheon Electronic Systems (RES), E-Systems, and the Commercial Group. The other three business areas are handled by each of the three other divisional business units, named according to the remaining key business areas in which they compete.

The discussion included in this thesis focuses primarily on RES, the divisional business unit which is chiefly responsible for Raytheon's defense-related products. Many RES core technologies hold tremendous potential value for dual-use application. The intention of the Raytheon-related sections of this thesis is to cite some dual-use technology examples in order to provide supporting data for illustrating the concepts of the multi-product adoption model presented in Chapter 3. This thesis does reveal any key elements of Raytheon's corporate strategy, nor does it make any specific recommendations concerning Raytheon's present or future operations.

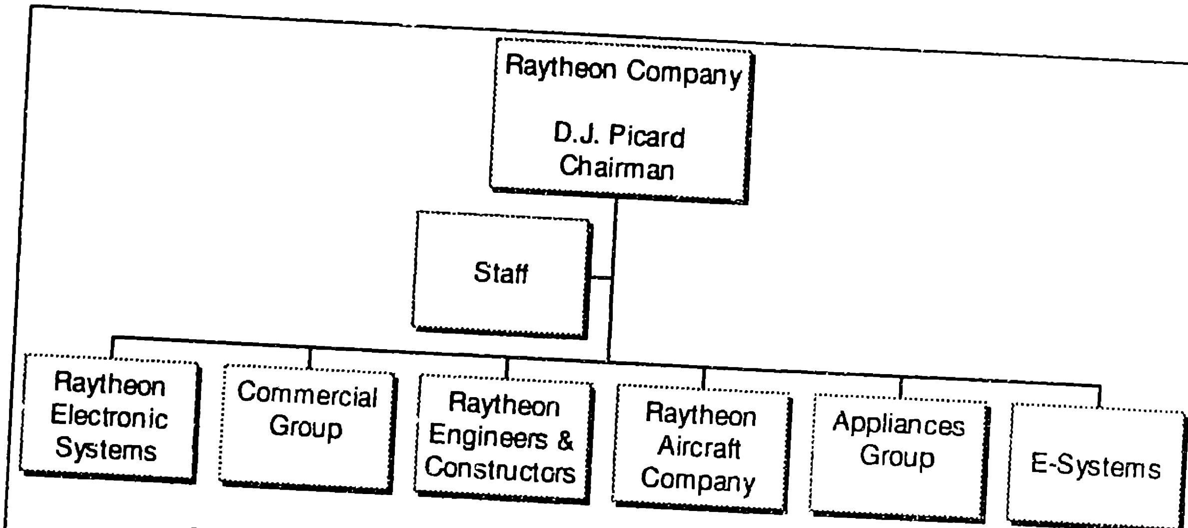

Exhibit A.2.2-1: Top-Level Raytheon Corporate Organization Chart

RES was formed in 1995 as the result of a merger between the two Raytheon divisions formerly known as Missile Systems Division and Equipment Division. Exhibit A.2.2-2 presents a brief description of major RES facilities and operation locations.

Exhibit A.2.2-2: Raytheon Electronic Systems Facilities Description

Location	Number of employees	Physical Size (ft^2)	Notes
Bedford, MA	1375	750,000	RES Headquarters
Tewksbury, MA	3350	670,000	Engineering Laboratories
Andover, MA	4554	1,255,000	Missile Manuf. & Assy.
Waltham, MA	2078	1,565,000	
Quincy, MA	680	260,000	
Marlborough, MA	1682	505,000	
Sudbury, MA	1331	527,000	
Portsmouth, RI	1055	569,000	
Bristol, TN	590	881,000	
Santa Barbara, CA	144	46,000	

Other operations in Huntsville, AL; White Sands, NM; Tulsa, OK; Littleton, MA; Wayland, MA; Waterloo, Ontario; Essex UK.

Source: *Raytheon Company New Hire Orientation Handbook*, 1995

RES is committed to compete in the defense sector and continues to apply defense technologies in commercial markets on a selective basis where there is a good match between the enabling technologies and market opportunities. The present emphasis of the division is to continue to provide innovative and cost-effective solutions to meet the needs of its worldwide customers. Costs have been lowered through consolidations, downsizing, and improvements in supply chain management. In Massachusetts, where most of the RES facilities are located, state taxes have been reduced through legislative initiatives, and lower electrical utility rates have been negotiated.

A.2.3 Raytheon Electronic Systems Distinctive Core Technologies

This section introduces top-level summary listings of several key technology areas within RES. The fundamental challenges in pursuing dual-use technology development involve managing technical risk, understanding core competencies, leveraging commonality across products and processes, exploiting existing distribution channels and marketing networks, and emphasizing the significance of customer "types." Each one of these challenges presents some level of controllable states and outcomes. The one which is often neglected in new market penetration is customer type.

In earlier discussions of this thesis, customer type was introduced as a decision parameter in expanding market applications for core enabling technologies. In the multi-product adoption model in Chapter 3, the issue of customer type will again be revisited. It suffices to say here that maintaining consistency in customer type can often reveal a "hidden" core competence when entering new markets as is often the requirement for launching dual-use technology product applications. Significant cultural issues exist in achieving successful new market penetration, and should be accounted, or at least recognized, before introducing the new product. New market entry can be accomplished in one of at least two different ways:

(1) Product introduction into an existing market where the firm has not previously competed;

(2) Gaining acceptance for a new product in an emerging market from a new customer type.

Whether the new product is a specialized high technology application such as a high-resolution high-speed infrared camera for secured night testing of military weapon systems, or if the product is a new $200 pair of basketball shoes, the cultural dynamics of the customer can limit the level of achievable success, even if the product has the greatest rubber soles in the world.

The remainder of this section presents several top-level summaries of RES technologies and areas of specialization. Exhibit A.2.3-1 presents a sample set of distinctive core enabling technologies; Exhibit A.2.3-2 illustrates several near-term technology growth areas; and Exhibit A.2.3-3 focuses down to several system engineering related technologies aligned with the system design and management components of this thesis.

Exhibit A.2.3-1: A Sample Set of RES Distinctive Core Enabling Technologies

Sensor Technology	Electro-Optical (E-O) Technology
Radio Frequency Sensors • Millimeter Wave Development (35 to 94 GHz) • Rugged Compact Packaging Laser Sensors • Low-Cost Solid State Designs • High Precision Imagery of Vehicle Motion, Power Lines, and Wind Conditions Infrared Sensors • Complete Design Capability (Detectors/Systems) Acoustic Sensors • Transducers and Hydrophones for Active and Passive Sonar • 150,000 Produced for U.S. Submarine Fleet	Fully Integrated Electro-Optical Organization • System Design, Development, and Production • Clean Rooms, Hardware-in-the-Loop/Dynamic Flight Simulator and Hardware Integration Facilities • Production Support High Performance Focal Plane Arrays (FPAs) • Indium Antimonide for Midwave • Mercury Cadmium Telluride for Long Wave • Two Color • Uncooled Detectors Amber Radiance Camera for Military and Commercial Applications* Laser Radars • CO_2 Laser Radar Systems • Wind Sensors • Underwater Imaging Systems • Precision Navigation Systems • Optical Phased Arrays • Integrated Optics • Eye Safe Low Cost Solid-State Designs Passive Infrared (IR) Systems • Passive IR Sensors/Seekers • Surveillance Systems • Search and Track Systems • High Resolution Imaging Sensors • More than 180,000 Sensors Manufactured

Source: *Raytheon Company New Hire Orientation Viewgraphs*, 1995

Exhibit A.2.3-2: A Sample Set of RES Technology Development Areas

MMIC*	Infrared (IR) Sensors	Wideband/Low Noise Systems
• Transmit/Receive Modules • AAW • Data Links • Digital MIMIC	• Detectors • Windows • Imaging Sensors • Non-Uniformity Correction	• Sources • Transmitters • Receivers • Diechoric Components • Synthetic Aperture Radars

Laser Systems	High Throughput Computers
• Agile Beam Director • Wind Sensors • Target Identification and Discrimination	• Multi-Chip Modules (MCM) • Multiple C-40s

* MMIC is an acronym for Monolithic Microwave Integrated Circuit

Source: *Raytheon Company New Hire Orientation Viewgraphs*, 1995

Exhibit A.2.3-3: A Sample Set of RES System Design Technologies

Battle Management C^3I Systems
- Data Fusion
- Command, Control, and Communication
- Interoperability
- Mission Planning and Terrain Analysis
- Automated Data Analysis

Total System Analysis
- From Requirements Definition to Effectiveness Evaluations
- Missile and Surveillance Systems
- Operations Analysis
- Life Cycle Cost Analysis

System Simulation
- Real-Time Hardware-in-the-Loop
- 6-Degree of-Freedom Simulations
- Pre-Mission Analysis
- Post Flight Reconstruction
- Force-on-Force War Gaming

Radar System Design
- Signal Processing Design and Analysis
- Discrimination and Target Algorithms

Missile Guidance and Control
- Aerodynamics
- Autopilot Design
- Warhead Evaluation
- Specialists in Guidance and Control Theory
- Propulsion
- Seeker Requirements Generation & Flowdown
- Integration and Test (Hardware and Software)

Foreign Technology Threat Assessment

System Integration and Field Testing

* For details of the Amber Infrared Camera technology/applications see Section 3.3.2.2 of this document.

Source: *Raytheon Company New Hire Orientation Viewgraphs*, 1995

A.2.4 Competitive Positioning Analysis

In order to complete the aerospace and electronics industry competitive analysis, a brief synopsis is presented to describe Raytheon's technological competitive response to the rapid and substantial decline in U.S. defense spending. This analysis of competitive positioning within the industry is intended to convey a glimpse into the fallout from a period characterized by mergers and acquisitions, and bring to bear the industry dynamics from the perspective of a moderate-size player in the competitive game.

From Raytheon's perspective, the series of mergers and acquisitions which have dominated the aerospace and electronics industries, at least in the defense sector, the ride has been reasonably gentle. Raytheon has chosen to grow stronger by buying small businesses rather than merging with a large partner. Raytheon's commercially-based diversification efforts have finally begun to balance the annual financial statistics, stabilizing defense sector volatility with revenues from commercial domestic and international markets. In the process, Raytheon has managed to steer a successful trajectory to becoming a diversified multi-industry global enterprise. According to a Forbes article in November 1995, Raytheon is the 19^{th} largest exporter in the United States, exporting $1.9 billion in 1994, a 9.5 percent increase over the previous year. Raytheon's major exports include electronic systems and engineering and construction projects. Exports represent 18.6 percent of total revenues for the company. Exhibit A.2.4-1 summarizes Raytheon acquisition purchases over the past several years. Exhibit A.2.4-2 and Exhibit A.2.4-3 present a short summary of events pertaining to the merger and acquisitions in the industry.

Exhibit A.2.4-1: Summary of Raytheon's Acquisition Growth Strategy Purchases [101]

- **August 1993**: Raytheon acquires Hawker, a division of British Aerospace for $372 million.
- **September 1994**: Purchases Xyplex Inc., a computer networking company for $172 million (sold in March 1996 to Whitaker Corporation for $117.5 million).
- **October 1994**: Buys UniMac. Company, a washing machine manufacturer for an undisclosed sum.
- **April 1995**: Acquires E-Systems Inc., for $2.3 billion.
- **July 1995**: Purchases Litwin Engineers & Constructors from United Dominion Industries, for $58 million.
- **April 1996**: Buys two defense and aerospace units from Chrysler Corporation for $475 million.

Exhibit A.2.4-2: Raytheon's Latest Acquisitions

Before the being acquired by Raytheon, E-Systems had grown rapidly to become the nation's premier vendor of high end electronic spy equipment to the U.S. military. With its activities grouped in categories that include reconaissance and surveillance; command, control and communications; navigation and controls; and aircraft maintenance and modifications, the acquisition presents a highly complementary business addition to Raytheon's high technology defense operations. Raytheon's bid on April 3, 1995 was $64 a share, a 41% premium over the going price. In 1994, E-Systems operating earnings were $178 million on sales of $2.03 billion.

Source: Boston Globe, 9 May 1995, "What does E-Systems mean for Raytheon?" David Warsh

In a move aimed at laying claim to a niche market in a defense industry increasingly dominated by behemoth corporations, Raytheon Company said it would buy most of Chrysler Corporation's defense and aerospace holdings in a deal worth $475 million. The purchase of Electrospace Systems and Chrysler Technologies Airborne Systems Inc., both Texas-based units of the Chrysler Technologies division, is part of a broad push by Raytheon into the fields of electronic-warfare, aircraft maintenance and overhaul, and secure communications. Chrysler Technologies Airborne Systems is a major player in the field of aircraft modifications, both civilian and military. Raytheon executives emphasized that the purchase would give them greater capability to offer one-stop shopping for aircraft hardware and software, complementing the services offered by E-Systems.

Source: Boston Globe, 9 April 1996, *Raytheon Beefs Up on Defense*, Jon Auerbach

Exhibit A.2.4-3: Northrop, Grumman, and General Electric; Lockheed, Martin Marietta, and Loral; Boeing and Rockwell

In 1995, Northrop Corporation acquired Grumman Corporation. Martin Marietta purchased General Electric's aerospace unit and General Dynamics' space systems division and then merged with Lockheed to form the world's largest defense contractor, with $23 billion in revenues. Lockheed Martin then acquired Loral bringing total annual revenues in excess of $31 billion. Lockheed's acquisition of Loral defense electronics facilities further expanded operations to manufacture such products as battlefield command systems and the computers used in jet fighters. Also in 1995, Northrop Grumman purchased GE's-Maryland based defense business for $3 billion.

Source: Aerospace America, March 1996 – *Mergers (again!), missiles, and more*, Robert Dore

On August 1, 1995, Boeing Co. agreed to buy the defense and space divisions of Rockwell International Corp. in a $3.2 billion deal in a continuation of the aerospace industry's consolidation into fewer but larger players. The transaction further recommits Boeing, the world's largest manufacturer of commercial jetliners, to its relatively modest military and space businesses. It also allows the Seattle-based company to compete more effectively with Lockheed Martin Corp. of Bethesda, Md., the biggest player in those fields, especially in work for the National Aeronautics and Space Administration. Several other industry players also had considered buying pieces of Rockwell lately, including McDonnell Douglas Corp., which is reportedly discussing a deal to buy Lexington, Mass.-based Raytheon Co.'s defense operations. Until now, Boeing had sat on the edge of the defense industry dance floor as more and more competitors paired off in mergers. "They see now they may not have another opportunity to make this kind of large buy" if they wait any longer, says John Kutler, president of Quarterdeck Investment Partners. The aerospace industry is undergoing another spurt of merger mania, he said. Besides reports of McDonnell's talks with Raytheon and plans for Rockwell, industry officials said the St. Louis company also considered a merger with Boeing in the last year.

Source: John Mintz, "Boeing to buy units of Rockwell", *The Boston Globe*, 2 August 1996

A.2.5 Managing Organizational Change—Three Perspectives

Organizational processes at Raytheon have been managed with direction and confidence. This section provides a brief overview of Raytheon's transition to a "New Model" organization. Analysis is presented from three fundamental perspectives—strategic design, political, and cultural. As United States industries experience a transition to a truly global marketplace, changes in corporate strategy and restructuring of organizations are commonplace among major companies searching for the optimal competitive policy to achieve sustainable competitive advantage.

Economic pressures to reduce cost and a market driven need to consolidate operations in the wake of the recent severe defense cuts in the United States have induced several initiatives to maintain competitiveness at Raytheon. By external measures, Raytheon's annual report and return to stockholders would suggest that the company is achieving desired outcomes. Annual sales in 1995 marked an all time high and strategic corporate diversification to commercial markets has been very successful. Internal investigation, however, reveals mixed member satisfaction from the perspective of many stakeholders including the employees. In order to identify and quantify the impact of the changes which have been implemented, the organizational analysis is discussed from three basic perspectives

A. Strategic Design
B. Political Perspective
C. Cultural Perspective

A. Strategic Design

The strategic perspective of an organization seeks to examine organizations under the assumption that they are "systems deliberately constructed to achieve certain strategic aims [1]." In order to understand the rationale behind organizational changes and cost savings initiatives at Raytheon, it is important to view the company situation as one of:

1. Strategic aim
2. Organizational structure
3. Organizational set analysis
4. Resulting change

From this approach, it is apparent that Raytheon has made substantial organizational changes to meet strategic objectives. Since organizational structure and analysis have been discussed in Section A.2.2, the objective here is to establish the strategic aim and recognize the resulting change.

Strategic Aim and Resulting Change

In response to the severe reductions in defense system procurement in the early 1990s, Raytheon initiated a strategic three-pronged approach to improve its competitive position, focusing resources to reduce costs on management, work force, and legislative fronts. Several principal competitors had recently moved to lower cost states to reduce operational costs. Hughes moved all missile manufacturing in 1993 to Tucson, Arizona and cut 6,100 workers. Loral moved Ford Aerospace production to Phoenix, Arizona cutting over 300 workers. Raytheon's message to its employees and the state of Massachusetts was clear—the company was committed to its Massachusetts roots and planned to fight to keep jobs in Massachusetts. The struggle would require significant measures to achieve its goals. Exhibit A.2.5-1 and Exhibit A.2.5-2 present a brief synopsis of the what Raytheon executives have coined "The Massachusetts Economic Situation."

The Massachusetts Economic Situation [78]

- Defense spending reductions throughout the 1990s severely impact the entire industry
- Other states offer incentives to attract major corporations to relocate manufacturing operations
- Raytheon 3-proged approach to increase competitiveness
    1. Management Initiatives (55%)
    2. Work Force Initiatives (35%)
    3. Legislative Initiatives (10%)
- Raytheon's strategy is to move from being a large defense contractor with some commercial business to a multi-industrial commercial company with a strong defense segment
- Over $200 million in defense conversion and dual-use initiatives
    - Air Traffic Control
    - Personal Rapid Transit
    - Iridium Satellite Communications
    - Vessel Tracking
    - SIVAM Environmental Systems in Brazil
    - Microwave Monolithic Technology/Center
    - Flat Panel Displays
    - Digital Telecon Technology

Exhibit A.2.5-1: Raytheon's Economic Situation for its Massachusetts-Based Defense Business

Source: *The Massachusetts Economic Situation*, Raytheon Viewgraph Presentation, 1994

Raytheon's 3-Prong Approach to the Massachusetts Economic Situation [78]

Raytheon's 3-legged approach to becoming more competitive includes management, work force, and legislative initiatives. Raytheon executives have created a "3-legged stool" analogy, representing the significance of all 3 legs being in place or the stool cannot function effectively.

- Management Initiatives
  - Consolidation of operations in Missile Systems Division and Equipment Division
  - Numerous plant closings, reorganization of Research Division
  - 1995 merging of Missile Systems and Equipment Divisions

- Workforce Contribution/Legislative Relief (Raytheon Rhode Island)
  - Introduction of Managed Care Medical Plans and Increased Employee Cost sharing
  - Wage reduction based on marketplace analysis
  - Reductions in number of job families and job titles (organizational flattening)
  - Worked with state to accelerate depreciation schedules, reduce taxes on energy, lower taxes

- Raytheon's Massachusetts Legislative Initiatives (Corporate Headquarters, Defense Electronics)
  - Single Sales Factor for Corporate Income Tax
  - Tax credit for retaining employees
  - Income tax credit for property taxes
  - R&D tax credit
  - Accelerated depreciation of new capital equipment
  - Sales/Use tax exemption for overhead material
  - Electric utilities cost relief
  - Other tax relief initiatives

Exhibit A.2.5-2: Raytheon's 3-Pronged Organizational Management Strategy

Source: *The Massachusetts Economic Situation*, Raytheon Viewgraph Presentation, 1994

Over the past several years, Massachusetts legislative initiatives have been highly successful. In addition to significant internal organizational changes and management initiatives to reduce operating costs, Raytheon's 1995 financial performance was impressive, logging in record sales complemented with a high level of success from commercial business segments.

B. Political Perspective

The political perspective of an organization is intended to "provide a way of mapping and interpreting different interests or goals that guide individuals, groups, or organizational units in decision making and a means of addressing the relative power of different participants [1].' Exhibit A.2.5-3 presents a perhaps insightful political perspective at a time of critical corporate decision making at Raytheon.

The Raytheon Case: When Good People Face Hard Choices [100]
An excerpt from the article written by David Warsh
The Boston Globe, 5 March 1995

Raytheon is the very model of the high-tech electronic enterprise that rescued Boston from its 19th century mechanical decline. It was put in business by the U.S. Navy in the years just after World War I to make reality of a new technology known as radio. From vacuum tubes, it moved on to help invent radar, moon probes and, eventually the famous Patriot missile. Along the way, Raytheon managers more or less invented diversification as a tactic to balance the cyclical nature their government earnings. Proud, effective, and above all, independent, Raytheon's strong and stable management rendered the company immune to the successive waves of takeover mania that wracked the defense business during the 1960s, 1970s, and 1980s.

Raytheon's three-legged strategic approach may be missing one aspect of the problem—the existence of a fourth hidden leg. The relative strength of the fourth leg matters greatly to the company's ability to make its missiles in Massachusetts. Its analysis involves the toughest long-term choices of all.

- At the moment, the style is really the extended shadow of one man, Raytheon chief executive Dennis J. Picard. Since taking over the firm from Thomas Phillips in 1990, Picard has managed the company in almost nothing but turbulent times, cutting back sharply on government operations, pushing forcefully into new civilian lines of business, and posting record earnings quarter after quarter throughout the process. By any standard, it has been a remarkable performance.

- Raytheon's own organizational structure; the state; and its wage earners all contribute to helping keep costs down. But the biggest challenge of all facing Raytheon and its union may be the composition of the Massachusetts congressional delegation, which overnight in November 1994 went from being a relatively powerful delegation to being one of the most impotent, by dint of its domination by Democrats. Here is to be found a hint of the fourth leg of an approach to competitiveness on which much of Raytheon's future must necessarily rest.

- Management is facing the same problem. For 45 years, Raytheon prospered by competing on the merits for the Pentagon's business, but in a pinch– when a rival sought to make a powerplay– there were powerful and efficacious members in the delegation willing to pay attention to Raytheon pleas, none more so than former House Speaker Thomas P. O'Neill Jr. Over time, the delegation's clout was one of the resources that strong management translated into record backlogs for the company.

Exhibit A.2.5-2: Raytheon's 3-Pronged Organizational Management Strategy

Source: David Warsh, *The Raytheon Case: When Good People Face Hard Choices*, The Boston Globe, 5 March 1995

C. Cultural Perspective

The cultural perspective of an organization "is intended to identify how history has shaped the assumptions and meanings of different people, how certain practices can take on special meaningfulness and even become rituals, and even how stories and other artifacts shape the feel of an organization. Deciphering organizational culture can be accomplished based on three conceptual categories—artifacts, values, and assumptions [1]." Specific focus for the cultural perspective here is the effects which have rippled through the lower levels of the organization as a result of the higher level response to external pressures to remain competitive. These effects are presented to identify an emerging cultural paradigm within some sectors of the company.

As organizations continue to consolidate operations and adjust corporate strategies to align with the changes in future technology needs, massive labor force reductions and major organizational restructuring has left many employees with perceptions of reduced career growth opportunities. Incentive systems which have traditionally relied on percentage-based annual salary increases linked to employee performance assessments can no longer maintain the levels which were commonplace during the high inflation period of the 1980s.

As with the movement to flexible manufacturing and platform-based design for products, employees must too be given transferable skill sets and portable competencies which are modular and compatible across multiple career applications to ensure that their value will continue to grow independent of market forces in a single industry.

Some Further Thoughts Based on the Three-Perspective Analysis

Although many people are quick to point out isolated weaknesses and challenges posed by a commonly held perception that Massachusetts is an expensive place to do business, a different perspective has recently been presented in a Boston Globe newspaper article by Lester C. Thurow, Professor of Management and Economics a the MIT Sloan School of Management. During these times of moderate recession compared to the technological growth which fueled the booming Massachusetts economy of the 1980s, people (and companies) are often overwhelmed with the messages claiming that other areas of the country are better places to do business. These messages are usually constructed on the basis of lower taxes or incentive structures which attract manufacturing jobs as opportunities for social and economic growth.

In the Thurow article [94], it is suggested that the "ultimate measure of economic success is per capita income. Using this measure of success, New England, and the Northeast more generally, do very well. Regionally, New England's per capita personal income was the nation's highest in

1995—$26,508 per person or 16 percent above the national average. The rest of the Northeast held the number 2 position, only slightly behind. The nation's top four states in personal income were all in the Northeast: Connecticut, New Jersey, Massachusetts and New York. New Hampshire was sixth. Looking at disposable income per capita, a measure that subtracts taxes, the facts remain unchanged. New England is still the No. 1 region, with disposable per capita income 14 percent above the national average [94]."

Thurow suggests that cutting energy costs is far more important than cutting state and local taxes, and that taxes can actually benefit the system in ways often difficult to capture with simple mathematical statistics and metrics. For example, a high quality educational system linked to the evolving needs of industry and the surrounding community is arguably highly valuable. "A good work force lowers business costs far more than any state or local tax cut and a good educational system helps persuade well-educated workers in the rest of the country that they should move to an area and get good education for their children [94]." Thurow's suggestions for understanding competitive position at a regional level are presented in Exhibit A.2.5-4.

Exhibit A.2.5-4: Issues for Understanding and Improving Competitive Position [94]

Develop a "sophisticated concern" as opposed to the simple "slash and burn" cut-the-government remedy so often suggested in recent times.

- Are there ways to reduce workers' compensation costs that don't cut benefits to those genuinely injured on the job?
- Are there ways to restructure energy markets to lower costs?
- Does our infrastructure give us the lowest possible transportation costs?
- Where lies the biggest bang for the buck in new infrastructure investments?
- What factors would lead New England to be seen as the best place for knowledgeable workers to develop their careers?
- What would make this [New England] an even better place to start up high-tech companies?
- Are there public services that we don't need or cheaper ways to provide those services we do need?

In each of these areas there are things that could be done to make New England a better place to do business. But as we do so, we should also remember that based on outcomes—the only thing that at ultimately counts—New England is already the country's best place to do business.

Source: Lester Thurow, "N.E. Business Sense," The Boston Globe, 16 July 1996

APPENDIX 3. CONTRACT TYPES

Firm Fixed Price (FFP) Contract

Description
- Price not subject to adjustment due to cost experience; maximum risk to seller
- Minimum administration burden on contracting parties
- No statutory limit on profit or fee
- Progress payments allowed under certain conditions

Application
- Suitable when definite design baseline and performance specifications are available
- Suitable when fair price can be established from available data

Observation
- May not result in lower price due to perceived risk by seller
- Changes can be costly
- Subcontractor may undesirably trade schedule, reliability, and quality against cost
- Least visibility into seller's cost and schedule position unless special provisions are negotiated

Source: MIT 16.870 Lecture Notes

Cost-Plus-Incentive-Fee (CPIF)

Description
- Negotiated target cost, target fee, minimum and maximum fee and fee adjustment formula based on actual cost, schedule, and operational performance
- All allowable, allocable, and reasonable costs incurred are paid
- An interim billing rate is normally allowable
- Statutory limits on earned fee exist
  - 15 percent of target cost for experimental, research, and development contracts
  - 10 percent of target cost for production contracts

Application
- Feasible for development situations
- High probability of achieving performance parameters
- Requires adequate accounting system for cost accumulation and auditing

Observation
- May result in lowest price contract: risk shared between buyer and seller
- Multiple incentive structure causes attention to buyer's objectives for cost control, schedule, reliability, and quality
- Beware of buy-ins if seller's objective is not profit
- Provides good visibility into seller's cost and schedule position

Source: MIT 16.870 Lecture Notes

Fixed-Price-Incentive (FPI) Contract

Description
- Negotiated target cost, target fee, and ceiling price
- Can provide fee adjustment for cost performance, schedule, and operational performance
- Interim billing rate or progress payments are normally allowable

Application
- Suitable when FFP is not feasible but circumstances are such that substantial cost responsibility belongs with the subcontractor
- FPI is higher risk to subcontractor than CPIF due to price ceiling
- \Requires adequate accounting system for cost accumulation and auditing

Observation
- Prior to the point of total assumption FPI is similar to CPIF
- After point of total assumption, FPI is similar to FFP; i.e., every dollar spent comes out of profit until ceiling price is reached. After ceiling price is reached every dollar the subcontractor spends to complete performance represents a loss.
- Provides visibility into seller's cost and schedule position

Source: MIT 16.870 Lecture Notes

Cost-Plus-Fixed-Fee (CPFF) Contract

Description
- Negotiated fixed fee based upon agreed-to estimated cost. Fee does not vary with actual cost experience
- Seller reimbursed for all allowable, allocable, and reasonable costs incurred
- Statutory limits on fee
  - 15 percent of target cost for experimental, research, and development
  - 10 percent of target cost for production

Application
- Normally only used in research, study, or development advancing the state-of-the-art with significant unknowns
- Requires adequate accounting system for cost accumulation and auditing
- Requires strong "management" of seller by buyer

Observation
- From buyer's point of view on cost: very risky and difficult to manage
- Should have restricted period of performance and dollar value. More controllable types of contracts used for follow-on periods

Source: MIT 16.870 Lecture Notes

Cost-Plus-Award-Fee (CPAF) Contracts

Description

- Negotiated target cost, target fee, minimum and maximum fee
- Actual fee is determined subjectively by the buyer based on periodic, after-the-fact evaluation of performance against specific criteria
- Award fee decision is unilateral, not subject to dispute
- Has a base fee normally between 0 and 3 percent
- All allowable, allocable and reasonable costs incurred are reimbursed

Application

- Trend is toward increased use on all types of contracts
- Sometimes included in CPIF contracts where appropriate motivation to management provisions are desired

Observation

- Keep award criteria genera; establish specifics at the beginning of each award period
- It is better to use CPIF if award criteria are limited to cost, schedule, and technical performance measurements
- Requires heavy administrative management effort to make it work
- If the subcontractor perceives his award as to low, he may be demotivated; if too high, he may become complacent with his apparent success

Source: MIT 16.870 Lecture Notes

Other types of variations on these contracts exist, several of which are listed below [43].

- Cost-plus percentage fee
- Cost-plus fixed fee
- Cost-plus guaranteed maximum
- Cost-plus guaranteed maximum and shared savings
- Cost-plus incentive
- Fixed price or lump sum
- Fixed price incentive
- Fixed price for services, material, and labor at cost
- Time and Material
- Bonus-penalty
- Combinations
- Joint Venture

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