Fostering Innovation Across Aerospace Supplier Networks

by

Aaron L. Kirtley

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ABSTRACT

The supplier base accounts for a large share of the total cost and technology content of major defense aerospace acquisition programs, such as the F-22 Raptor. Also, a significant share of technological innovation across many industries takes place at the interface between customer companies and their suppliers. This research seeks to determine what incentives, practices, and tools aerospace companies can employ to foster greater innovation across their supplier networks, thereby optimizing weapon systems' performance and affordability. It also attempts to understand how the defense contracting policies of the US government may encourage or act as barriers to innovation in supplier relationships. These questions are addressed through in-depth case studies focused on two major avionics subsystems of the F-22 Raptor. The case studies explore the interactions between the prime contractor, major subcontractors, and sub-tier suppliers involved in the subsystems' design, development, and production.

This research highlights the importance of encouraging collaboration and understanding the interdependencies between members of the extended supply chain. Analysis of the case studies suggests that major drivers and enablers of supplier innovation include (1) good two-way communication, (2) joint funding of investment projects, (3) training and support, (4) incentive mechanisms built into contract structures, and (5) appropriate levels of competition. Barriers to supplier innovation include uncertainty about the program's future, concern for secrecy and protection of classified information, the concurrency of design and development efforts with production, and government contracting practices that often fail to reward innovative efforts. Along with modifying some of its funding practices and regulations, the acquisition community can help to spur innovation across the aerospace supplier base by providing support for improvement projects and direct funding of research, development, and technology transfer in critical technology areas. In turn, a more innovative supplier base has the potential to enhance the affordability and reduce the lifecycle cost of ownership of weapon systems in significant ways.

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I have been richly blessed during my stint at MIT with many wonderful friends who have provided inspiration, broadened my horizons, and truly made my time in graduate school fun. A special thanks to Pradeep, my roommate and officemate for two years, for Indian cooking lessons, thesis advice, and many good memories. Michelle, thanks for your encouraging words, excellent editing assistance, and much more. Thanks also to my mom, grandpa, and the rest of my family for their continual support, love and prayers through the years, without which I could never have attained this milestone in my educational career.

Finally, praise and thanks be to my Lord and Savior, Jesus Christ, creator of the universe and ultimate supplier of all innovation.

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1 INTRODUCTION

1.1 BACKGROUND

The strength of modern military power depends heavily on advanced technology. A nation able to leverage advanced technology into military might will be better positioned to defend and promote its strategic interests both at home and abroad. Therefore, the U.S. military continually seeks to acquire and maintain state-of-the-art weapon systems. As defense budgets have declined over the past decade and weapons' costs have escalated, this endeavor has become increasingly difficult. To maintain the nation's military edge, domestic defense contractors must be innovative, both in developing new, better-performing weapons systems and in finding ways to produce them more cheaply. This challenge to produce new technology at lower costs applies not only to the few major prime defense contractors in the aerospace industry but also to the numerous subcontractors and suppliers that comprise the larger aerospace supplier base. Meeting this challenge requires developing and tapping the innovative potential of thousands of firms that manufacture aerospace products, which are ultimately integrated into complex, high-tech fighter jets, missiles, and spacecraft. This research examines methods of incentivizing and nurturing innovation in the aerospace supplier base in order to reduce the cost and improve the performance of weapons systems. For the purpose of this research, ***innovation*** refers to the implementation of new ideas that improve a product or its production process and ultimately result in greater value to the customer through better performance, higher quality, greater longevity, or reduced cost.

1.2 PROBLEM CONTEXT – THE DEFENSE AEROSPACE INDUSTRY

The world aerospace industry has traditionally depended heavily on defense spending as a major source of its revenue base and as a source of its technological progress. This has particularly been true in the United States, where the purchasing power and procurement procedures of the federal government have fundamentally shaped the nature of the industry. A large portion of the aerospace industry's R&D dollars has traditionally come from the U.S. government for defense purposes. Both the size of the defense budget and the terms under which the government contracts out its defense work have dramatically affected the level of prosperity in the industry.

Over the past decade, defense budgets have declined considerably from previous Cold War levels. Coupled with these cutbacks has been an emphasis on acquisition reform, designed to achieve significant affordability improvements in weapon systems acquisition. The sharp fall in demand for new defense aerospace systems has forced many aerospace companies to restructure and streamline their businesses to achieve greater efficiency gains in order to stay in business in the face of falling total revenues and profits. Other companies have simply closed up shop. Recent years have seen a major consolidation both among prime contractors and second- and third-tier suppliers. Some suppliers have divested themselves of all defense-related contracts to focus solely on the commercial market. Others have joined together to form larger companies possessing a broader range of skills, in the hopes of positioning themselves to attract any remaining defense business. Along with this industry contraction, many firms have considerably reduced their R&D funding, generating concern about the loss of the U.S. industry's technological edge.

Affordability has become a keyword in the defense industry today. Defense personnel began to realize in the 1980's that if the spiraling weapons costs continued, maintaining a broad and technologically advanced arsenal would soon become financially infeasible. Norman Augustine, former CEO of Lockheed Martin, captured the essence of this problem when he predicted in 1988 that if the cost of tactical fighter jets continued to grow according to past trends, purchasing one new fighter in 2054 would consume the entire defense budget (Sweetman, 1998 p.11). The emphasis on affordability has prompted the government to take a new look at its relationship with industry, and prompted industry to re-examine its processes and search for new ways to eliminate waste and deliver greater value to its primary customer. Many companies have turned to the principles of lean manufacturing learned from the Japanese automotive industry to streamline their production systems. The government's focus has shifted somewhat from acquiring leading-edge technology at any cost to acquiring new, but proven technology at affordable costs.

The revolution in microelectronics over the past decade has also shaped the defense industry in new ways. Following World War II, defense funding was the driving force behind high-tech research. The federal government was the primary customer of sophisticated electronics devices such as semi-conductors and microchips. Therefore, it possessed great leverage over high-tech manufacturers and shaped the direction of technology. Today, however, much of the technology developed for military applications has found its way into a wide range of sophisticated commercial products. The government is no longer a major customer for most suppliers of microelectronics, which have discovered a lucrative and expanding commercial market for their products. In contrast to the commercial market, the defense market demands very low-volume, highly customized components. These components are typically much more expensive than their commercial variants. The exacting environmental requirements that many military electronic components must meet, coupled with the additional contract-related transaction costs and low profit margins often imposed by defense acquisition regulations, is enough to deter many potential suppliers. Yet performance of defense aerospace products (planes, missiles, satellites, etc.) increasingly depends on integrating the latest electronics, networking, and sensor technologies, most of which are being developed for commercial uses and must be adapted to military applications. The cost of acquiring this technology continues to soar.

Military products, such as fighter planes and missiles, have relatively long lifecycles, making it more difficult to keep their technology up-to-date. While the effective service life of a typical microprocessor is only 3-5 years before it is replaced by new technology, planes using this chip in their avionics systems will be manufactured over a 10-year or longer period and will be expected to remain functional for 25-40 years. Acquiring microprocessors to repair avionics systems several years after production has ceased can be extremely difficult, if not impossible. Often the original manufacturer of the microprocessor no longer exists. The cost of redesigning the system to incorporate the newest version of technology is usually very high. Defense contractors manufacturing fighter jets face the challenge of integrating fast clockspeed avionics technology into slower clockspeed airframes. The rapid pace of technological change and the decline of the aerospace supplier base have created a major parts obsolescence problem. Both in production and maintenance, prime contractors and the Air Force are faced with diminishing manufacturing sources (DMS) for many avionics components. The costs of obsolescent parts and DMS threaten to consume a significant portion of defense funds, meaning fewer resources for investment in newer technologies. While there is no silver bullet to solve DMS problems, contractors must continue developing innovative new approaches to mitigate them, including increased use of commercial off-the-shelf (COTS) components, open architecture designs that allow easy upgrades, and greater communication with their suppliers.

1.3 LEAN MANUFACTURING AND NEW APPROACHES TO MANAGING SUPPLIER NETWORKS

As a result of recent changes in the aerospace industry and the focus on greater affordability, companies have begun adopt new methods and strategies to minimize waste, reduce costs, and improve lifecycle value. Many have turned toward lean manufacturing principles, first practiced by the Japanese and more recently applied with relative success in the U.S. automotive industry. Moreover, the defense acquisition community and aerospace prime contractors have come to realize the crucial role suppliers must play in achieving greater affordability. The supplier base accounts for much of the total cost of major defense aerospace acquisition programs. For example, suppliers account for approximately 60% of the total cost of the F-22 Raptor[1]. Thus, new approaches to supply chain management are emerging in the aerospace industry. In the past, the major aerospace companies held an arms-length view of their supply chain. In dealing with suppliers, they sought to use their size and influence as leverage

[1]Presentation by Chris York, Boeing Aircraft and Missile Systems, at F-22/F-119 Executive Supplier Conference, June 8-10, 1999.

to maximize their buying power. Suppliers were played against one another and squeezed to obtain the lowest possible price. There was little commitment by major firms to their suppliers. There has been a fundamental shift, however, and major companies have begun to see a strong supply chain as fundamental to their own success. A new model of closer supplier relationships, collaborative design, and Japanese-style partnerships has begun to take hold. While there seems to be consensus in the literature and among firms that this model is superior to the older, arms-length approach, the model is continually evolving. Companies are still trying to determine the specific ways in which this model should be applied to their supply chains and evaluate the potential sources of benefit. Many firms have developed just-in-time inventory systems and arranged for supplier deliveries directly to the factory floor. Prime contractors have taken steps to train their major suppliers to implement lean practices. Some have begun helping suppliers restructure their manufacturing systems to reduce cycle time, floor space, and workpiece flow.

1.4 RESEARCH FOCUS

While managers at major aerospace companies have largely learned and adopted the basic tenets of traditional factory floor lean and the logistical aspects of supply chain management, it is only more recently that they have begun to consider their supply chains as part of an extended enterprise. This has raised larger questions pertaining to the design and management of supplier networks as a means of creating value and enhancing competitive advantages. It is these larger questions that this thesis primarily seeks to address. In particular, there is great potential for technological innovation to occur at customer-supplier interfaces. The following chapters explore ways through which companies can exploit this potential and develop supplier relationships rich in innovation. The central goal of this research is to identify incentives, practices, and tools aerospace companies can employ to foster innovation across their supplier networks.

It should also be noted that within the defense industry the behavior of the U.S. government and defense acquisition community often has a major impact on the behavior of firms. The interactions between customers and suppliers in the industry cannot be fully understood outside of this context. Therefore, this thesis also considers ways in which defense contracting policies and practices may encourage or act as barriers to innovation in supplier relationships. Ultimately, it is hoped that this thesis will provide useful insights and tools for defense aerospace companies to more effectively manage their supplier networks. Additionally, it is intended to provide government officials and acquisition personnel a greater understanding of how defense policies can best support these companies in their effort to provide weapon systems that optimize performance and affordability.

1.5 OUTLINE OF CHAPTERS

Chapter Two will discuss more specifically the central questions this thesis seeks to answer and describes the research methods employed in this effort. Chapter Three provides background information about the F-22 program, which forms the central focus for the research. It also summarizes lessons learned through a comparison of several different fighter programs, based on discussions with individuals involved in these programs at Lockheed Martin. Chapter Four reviews the major themes in the literature pertaining to drivers of supplier-based innovation in customer-supplier relationships. Chapter Five contains a case study on the F-22 Radar and the major subcontractor involved in its production, while Chapter Six involves a case study of the F-22 Electronic Warfare Suite and the subcontractor responsible for this subsystem. Chapters Seven and Eight discuss the characteristics of eight subtier suppliers that produce critical components for the Electronic Warfare Suite and the Radar and explore the nature of these suppliers' relationships with the major subcontractors. Chapter Nine then analyzes the major lessons and themes that emerge from the case studies described in the preceding chapters. Finally, Chapter Ten summarizes the major findings and conclusions of this research.

2 RESEARCH DESIGN AND OBJECTIVES

2.1 INTRODUCTION

The focus of this research evolved over a two-year period. During this time a sharper picture of the industry context was developed, leading to a clearer understanding of the central questions confronting defense aerospace companies in their endeavor to build lean supplier relationships. Through review of the literature and discussions with many individuals in industry, academia, and the government, the key issues were identified and the approach to investigating them was defined.

2.2 INITIAL RESEARCH DIRECTIONS

When this study began, it initially set out to examine the evolution of supply chain management practices in the defense aerospace industry, focusing in particular on the F-16 Fighting Falcon. The F-16 was chosen based on its long history and reputation as a robust, durable, and adaptable fighter that has delivered superior value to its customers worldwide. It was hoped that the F-16 would offer a rich opportunity for observing the ways in which technological breakthroughs and innovative practices by suppliers had contributed to the continual success of a program. Furthermore, there was interest in observing how customer-supplier relationships, the defense environment, and the nature of the supply base had enabled and stimulated such developments. After discussing these objectives with program personnel at Lockheed Martin, however, it became clear that a study focused solely on the F-16 was too narrow. The bulk of F-16 production had occurred over the past three decades in an industry environment very different from that prevailing today. While good lessons could certainly be drawn from studying the F-16's history, managers wanted more than a historical perspective and richer research opportunities became evident.

2.3 A CROSS-PLATFORM STUDY OF AVIONICS SYSTEMS

Managers of major defense aerospace companies were interested in identifying creative, new approaches to supply chain management appropriate for the unfolding industry conditions of today and tomorrow. The new environment features unprecedented opportunities and challenges as technology rapidly advances but becomes more expensive, while at the same time government funding priorities and practices undergo major transitions. Therefore, managers proposed a cross-platform study that included the more recent F-22 and Joint Strike Fighter (JSF) programs along with the F-16. The study would focus on the avionics systems of each of these planes, which are major contributors to both aircraft performance and cost. Avionics systems present special challenges to contractors due to their increasing technological sophistication and the rising share of total lifecycle cost of ownership they represent.

Several additional site visits to Lockheed Martin were made and a wide range of individuals involved in the F-16, F-22, and JSF programs were interviewed. This provided valuable background information on the historical development, current status, and long-term goals of each of these programs, along with industry perspectives on the major challenges and successes encountered along the way. A number of important insights were developed about how different approaches to avionics system architectures, technology choices, and supply chain management have shaped program outcomes, while being influenced by program objectives and environments. Chapter 3 describes these insights and summarizes the lessons learned through this comparison of fighter platforms, forming the basis for what eventually became the more specific focus of this thesis. After developing the background for a cross platform study of avionics systems, it was determined that this topic was too broad to be explored fully within the timeframe available. While the study's premise was very appealing, acquiring and assimilating the detailed information necessary for conducting a thorough analysis was not possible. In some cases, the data remain classified and would not have even been accessible. As a result, it was decided to narrow the focus to the F-22 program.

2.4 FOSTERING SUPPLIER INNOVATION AND THE F-22 PROGRAM

The F-22 program began in the early 1980's, but only recently received the "go ahead" decision for low rate initial production. Early discussions with program personnel revealed that while the F-22 program represented an impressive technological achievement, there was growing concern about parts obsolescence and the plane's affordability. An obvious area of focus for this study seemed to be the F-22 supply chain supporting the avionics system, which accounts for a large share of the plane's technology and cost. The decision was made to study the sources and stimulants of innovation among F-22 suppliers. As one of the most important defense programs currently in production, it was felt that studying the F-22 would provide valuable insights into the state of the defense aerospace industry and the nature of relationships between the DoD, major contractors, and suppliers in today's contracting environment. Based on early discussions with industry and government personnel, it appeared that the F-22 typified many of the new challenges and obstacles that have emerged in recent years within the defense community, and which are expected shape the development and production of weapons systems in significant ways in years to come. As a result, this major program seemed to be a natural subject of inquiry in the quest to identify new strategies for improving the process of designing, manufacturing, and procuring critical defense systems and products.

As defense programs strive to achieve ever more ambitious performance objectives and affordability goals, the importance of a closely integrated supply chain has become increasingly clear. Supply chain integration implies a network of collaborative and mutually supportive relationships at each tier of a program's supplier base, which leads to better coordination of efforts among customer companies and their suppliers and helps to optimize the design and production of the final product. Within the supply chain there is great potential for innovation to occur at customer-supplier interfaces. Realization of this potential, however, depends in large part on the customer company's effective management of its supplier relationships. The desire to encourage supplier innovation raises important questions about how companies should relate to their suppliers and how they should structure their supplier networks. The attempt to answer these questions led to this study, which was framed around the following core question:

What incentives, practices, and tools can aerospace companies employ to foster innovation across their supplier networks?

Here, innovation has been broadly defined as the implementation of new ideas that improve a product or methods by which it is produced, ultimately resulting in greater value to the customer through attributes such as better performance, shorter lead time, higher quality, greater longevity, and reduced cost. Based on a review of the literature and discussions with industry experts, a number of hypotheses that could be tested in the context of the F-22 program were developed about potential enablers of, and incentives for, supplier innovation. These hypotheses are detailed in Chapter 4 and include ideas such as better methods of communication, sharing of investment expenses, training, and contractual incentives. Specific categories of questions include: What forms of communication between customer companies and suppliers are most conducive to innovation, and in what ways can communication become more effective? To what extent is risk sharing or financial support of supplier investments by the customer essential to enabling innovation? Does supplier training by customers play an important role in spurring innovations in manufacturing techniques and processes? In what ways can contract structures be designed to motivate suppliers to innovate? What common barriers to innovation currently exist in supplier relationships and how can they be overcome? What role does the defense acquisition community play and how does the defense environment affect the process of supplier innovation?

In studying innovation in the context of supplier relationships, this research was less concerned with determining specific sources of innovations or examining how innovations were acquired. In other words, this research did not probe issues such as categories and levels of R&D funding, technology licensing practices, employee creativity, or market research methods. Instead, it focused primarily on customer-supplier interfaces. It sought to understand the interactions between the customer companies and their suppliers, the means and mechanisms employed for managing these interfaces, and how these in turn may impede or foster greater innovation. In seeking to address the key questions just posed, companies were asked about specific facets of their relationships with important customers and suppliers, with an eye towards determining which relationship characteristics and practices may have provided an important stimulus to innovation. It was hoped that this emphasis on the customer-supplier interface would provide valuable insights into how these interfaces can be improved or redesigned in the future to create environments more conducive to innovation.

The concept of customers employing strategies specifically designed to foster greater innovation across their supplier networks is a relatively nascent one. Although considerable research exists on the topic of managing supplier relationships, there has been little discussion in the literature pertaining to the proactive fostering of supplier innovation. From the evidence available, the thrust of Toyota's supply chain practices seems to have been the attainment of continuous, incremental performance improvements. It is difficult, however, to pinpoint cases in which Toyota has proactively sought to cultivate innovation among their suppliers. In fact, the "lean" mindset is typically centered around ideas of waste minimization and efficiency improvements, but has little to say about technological innovation. This uneasy relationship between innovation and lean concepts becomes apparent when looking at much of the defining literature on principles of lean manufacturing. For example, the index of Fujimoto's major work ***The Evolution of a Manufacturing System at Toyota*** bears no reference to innovation and widely read ***The Machine That Changed the World*** only briefly mentions "lean innovation" to characterize the Japanese practice of incorporating preexisting inventions (such as superchargers and double-overhead camshafts) into their engine designs to enhance performance. This research, however, seeks to augment this traditional conceptualization of the lean model by examining customer-supplier interfaces from the perspective of innovation.

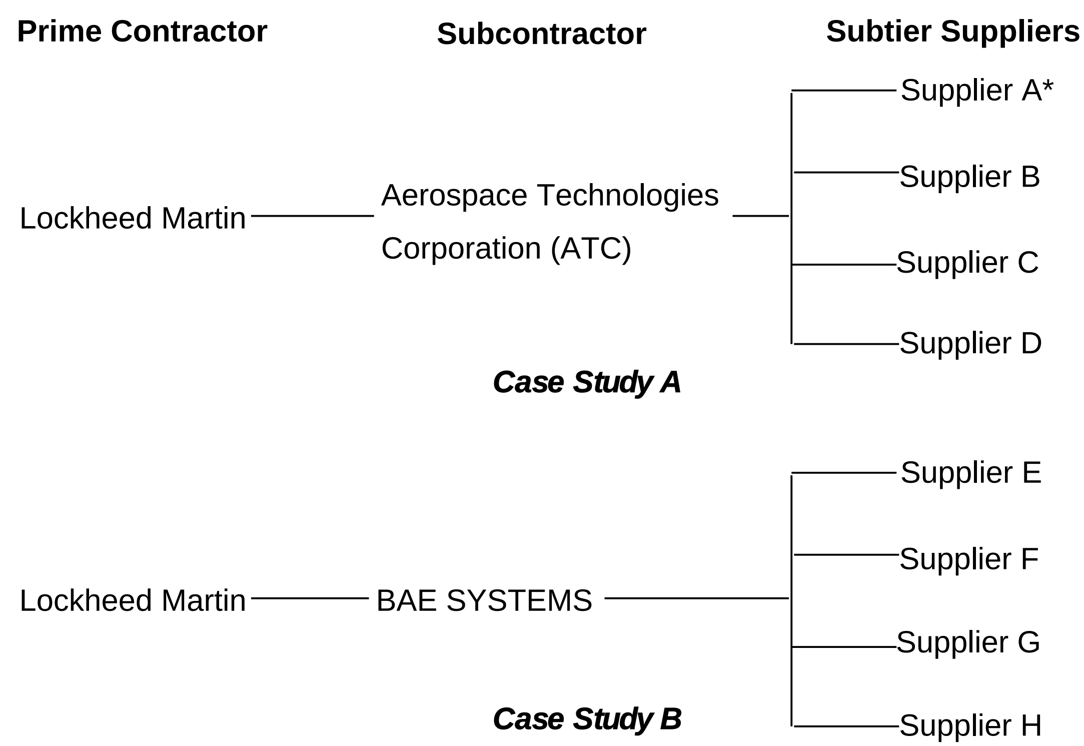
2.5 RESEARCH APPROACH

Several different approaches were considered in seeking to address the research questions posed above. These included industry surveys and case studies. It was eventually determined that the latter were best suited to the exploratory nature of the research. Case studies provided the flexibility to capture a richer set of concrete and contextually-grounded data and adapt the research focus to home in on those issues that emerged as being the most significant. It was hoped that in addition to helping determine the validity of the hypotheses regarding supplier innovation, the case studies would provide an in-depth picture of current supply chain practices within the industry. This would then enable the development of a framework for more comprehensive survey in the future targeting the extended defense aerospace supplier base and helping to prove more specifically and quantitatively the drivers of innovation.

Comparing the differences in innovation sources and incentives between commercial and defense supply chains was initially considered as a potential research strategy. These case studies would focus on companies that supply similar items under both commercial and defense contracts and examine their relationships with their respective customers. It became evident, however, that identifying appropriate comparable cases would be very difficult, as significant differences typically exist between avionics items for defense and commercial purposes. In fact, even across defense programs, differences in program objectives (e.g., in terms of stealthiness, supercruise capabilities, aerodynamic agility) and time periods lead to markedly different product requirements, making comparisons difficult. Other important parameters that differ across aerospace products and programs include the number of units produced, mission goals, and product and program life expectancy. Therefore, it was decided that restricting the case studies to a single defense program would be best.

2.6 STUDY DESIGN

Through discussions with engineers and managers at Lockheed Martin, four major subsystems that comprise the F-22 avionics system were identified: the radar, the communication, navigation, identification unit (CNI), the electronic warfare (EW) suite, and the central integrated processor (CIP). Separate subcontractors are responsible for supplying each of these avionics subsystems. Two of these subcontractors agreed to participate in in-depth case studies focusing on their involvement in the F-22 program. These two subcontractors supply the F-22's radar and EW suite, and both derive the majority of their revenues from defense-related products. Four of the key F-22 subtier suppliers of each subcontractor were also selected to participate in these two case studies. These eight subtier suppliers were chosen according to the nature of their business, their location, and suggestions from subcontractors. An attempt was made to focus on representative suppliers that produced avionics-related electronics and were also relatively accessible for field research. These companies are described in greater detail in later chapters. The case studies were laid out as shown in Figure 2.1. The real names of the majority of companies involved have been disguised in order to provide anonymity. By interviewing individuals at the prime contractor, two major subcontractors, and eight subtier suppliers, the aim was to examine a representative cross-section of the larger avionics supplier base and compare perspectives across different tiers of suppliers.



* Supplier A is also a key supplier of printed circuit boards to BAE SYSTEMS, so researchers were able to include perspectives on its relationship with this customer as well.

Figure 2.1 – Layout of Case Studies

2.7 RESEARCH METHODS

During the initial stages of the research, unstructured interviews were conducted with a wide range of individuals at Lockheed Martin over the course of three site visits to its production facility in Forth Worth, Texas. These individuals included engineers, material managers, purchasing specialists, and other personnel involved in the F-16, F-22, and JSF programs. In addition, telephone interviews were conducted with several buyers of critical avionics components and subsystems. Through the site visits and telephone interviews, a clearer understanding of the prime contractor's relationship with suppliers and the key issues relating to supply chain management was gained. The broad exposure to several programs across the prime contractor's organization enabled the thesis question to be refined and helped to narrow the focus to the F-22 program.

Once the research focus and key research questions were defined, two versions of a standard questionnaire were developed to structure further interviews. A shorter version was used for all interviews with subtier suppliers, while the other was used during interviews with subcontractors (Appendix A). Questions probed the company's relationship with both its supplier and customer over the course of its involvement in the F-22 program. After developing the questionnaire, visits were made to the Aerospace Technologies Corporation and BAE SYSTEMS facilities where the F-22 radar and EW suite, respectively, were designed and produced. Eight people at Aerospace Technologies Corporation and seven people at BAE SYSTEMS were interviewed, including program managers, design engineers, manufacturing engineers, material managers, and contracts managers. The goal was to capture the full range of perspectives and experiences across each company as they related to the F-22 program. The interviews with each individual lasted approximately one hour. In a few cases, two or three employees were interviewed simultaneously due to schedule constraints. Due to differences in areas of expertise, all parts of the questionnaire were not equally applicable to each individual. Over the course of interviews, however, answers were able to be obtained to all questions on the questionnaire. The author and his thesis supervisor took written notes of each interview, and these notes were compared to ensure consistency in the data. Upon completing interviews at the two subcontractor organizations, visits were then made to each of the eight subtier suppliers. At each site, at least one interview with a senior staff person knowledgeable about the supplier's relationship with the customer and at least one senior staff person familiar with the technical aspects of the supplier's F-22-specific product was requested. Each interview was structured according to the standard questionnaire developed for subtier suppliers and lasted approximately two hours.

In addition to notes taken during the interviews, some organizations provided supplementary documents providing more detailed information. These documents included lists categorizing major suppliers, background information about the company and its products, and descriptions of recent initiatives involving suppliers or customers. Most of the organizations also maintain Internet websites, which provided general information that could also be referenced. When available, these supplemental sources were also used in writing the case studies.

2.8 VALIDITY AND ANALYSIS OF DATA

Efforts were made to structure the research in a manner that would ensure validity of the data and observations collected. It was felt that the two and a half years over which the study was conducted provided sufficient time to frame the study and develop a clear understanding of the defense aerospace supplier base. Over a year was also spent refining the research focus, which helped to ensure a firm grasp of the critical issues and confirm that the right questions were being asked. Standard questionnaires were used to structure the interviews and ensure uniformity in the questions asked of each organization. The questionnaires were e-mailed to the point of contact at each organization that participated in the study prior to on-site interviews. At the start of each interview, the research objectives were explained and a definition and examples of innovation were provided to make certain interviewees understood the context of the questions. It was made clear to the individual interviewees that the interviews would be conducted on a “not-for-attribution” basis and that the individual interviewees would not be identified by name. Moreover, individual companies were informed at the outset that they would not be identified by name without their specific permission. Further, all interviewees were informed from the outset that their responses would not be used to grade or score individual or company performance, but only for research purposes. This was done to encourage participants to be forthcoming with potentially controversial or negative information. In the interviews, attempts were made to ask the questions in an unbiased manner and record respondents’ answers in their own words to the greatest extent possible. An effort was also made to clarify points of ambiguity through follow-up questions. Summaries of the interviews were later provided to each organization’s point of contact to confirm the accuracy of the data collected.

The research is sponsored by the Lean Aerospace Initiative, a consortium of industry, government, and labor, with the Massachusetts Institute of Technology acting as the neutral research arm of the group. It was hoped that the academic nature of the research, conducted under the auspices of MIT, would provide an unbiased perspective for all parties involved. All interpretations of facts given in the thesis are those of the author and they in no way represent the position, opinion or perspective of MIT, the US government agencies, companies or labor organizations sponsoring or participating in the Lean Aerospace Initiative.

In analyzing the data, attempts were made to carefully weigh all perspectives and observations pertaining to particular hypotheses or aspects of the research question. The on-site interviews were followed up with e-mails and telephone calls to interviewees where necessary to clarify points of discrepancy in the data and verify important details. Generalizations in the case studies represent convergent observations from multiple individuals or organizations. Where observations are based on comments from only one individual or organization, this is noted in the analysis.

3 BASIS FOR RESEARCH

3.1 IMPORTANCE OF AVIONICS IN FIGHTER AIRCRAFT

Modern fighter aircraft increasingly depend on advances in avionics for both their affordability and performance. In recent years, rapid advances in electronics technology have spurred the avionics advances that dramatically enhance the capabilities and performance of today's warplanes. At the same time, avionics systems represent the single largest component of weapons system cost and are consuming an ever larger fraction of the total. Including software, avionics will account for over 30 percent of the future Joint Strike Fighter's flyaway cost and a similar percentage of the F-22's cost (Groat, et al; 1997). This is shown in Figure 3.1, where both these platforms fall into the "New Systems" region. A key challenge faced by companies in the defense industry is

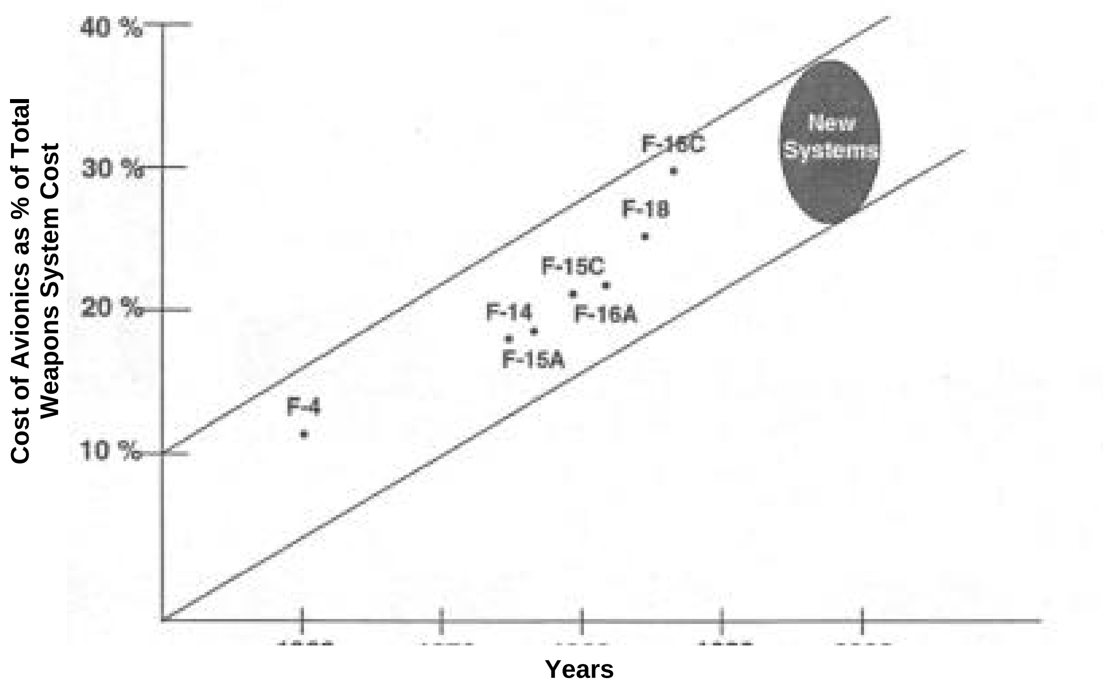


Figure 3.1 – Increase in Avionics Costs[2]

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[2] Based on: Joint Advanced Strike Technology Program - Avionics Architecture Definition Appendices - Version 1.0, p. B-4

how best to stimulate and tap supplier-based innovations to achieve lifecycle affordability of weapons systems while also maximizing continuous performance. This research seeks to address this issue by providing insights into how companies can strategically manage their supplier networks to achieve these goals. Because it has come to assume a central role in terms of technological complexity, scope and speed of technological change, and total acquisition cost, the area of avionics provides an important context for examining supply chain management issues. However, it is hoped that many of the lessons drawn from this work can also be applied beyond avionics in addressing a broader array of supply chain management challenges in the aerospace industry.

3.2 THE F-22 RAPTOR

The F-22 Raptor was chosen as the central focus for the case studies described in the following chapters. To provide a perspective for these case studies, it is first helpful to consider the characteristics of this major defense acquisition program in context of the evolutionary development of avionics systems and related supplier integration issues. The F-22 emerged from a competition between three major aerospace companies in the 1980's to design a new air superiority fighter to replace the aging F-15 Eagle. The plane has been under development for nearly 20 years, at a total program development cost of over $20 billion (GAO/NSIAD-00-68). In 1991 an industry team of what was then Lockheed and Boeing were awarded a $9.55 billion contract for the engineering and manufacturing development (EMD) phase of the program, which has since increased to due to various changes (FAS website). Lockheed Martin serves as the final assembler and prime contractor for the program, while Boeing is responsible for producing the wings, aft fuselage, and several other portions of the plane, along with operating the Avionics Systems Integration Laboratory. The EMD phase of the program will be completed by 2003. Concurrent with EMD, production has begun on 8 production readiness test vehicles (PRTV I and PRTV II), as well as 10 planes that are part of production Lot 1. A tentative production schedule for the F-22 is shown in Figure 3.2. The schedule has been modified a number of times since EMD began in 1991 due to a series of funding problems in light of cutbacks in defense spending. The Raptor is scheduled to actually enter service in 2005.

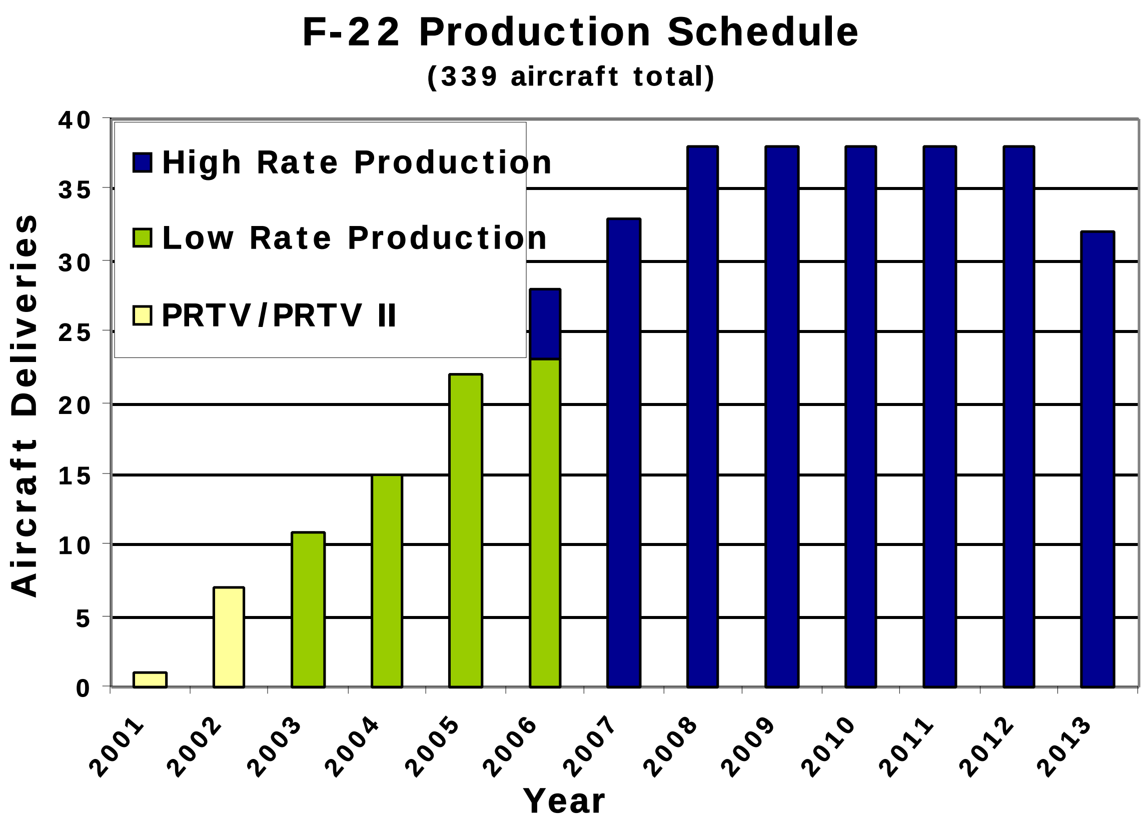

Figure 3.2 – F-22 Production Schedule[3]

3.3 ADVENT OF AN INTEGRATED AVIONICS ARCHITECTURE

As a replacement for the F-15 Eagle, the Raptor was designed to be the next generation air-superiority fighter for the US Air Force, with air-to-air combat capabilities exceeding those of any other plane in the world. To achieve its "first-look, first-shoot, first-kill" design specifications, the Raptor features advanced aerodynamics, leaps in stealth technology, and supercruise engines. However, as David Brown of ***Aviation Week*** states: "Of all the advances engineered into the F-22, the integrated avionics

[3] Based on F-22 Program Master Schedule No. 26, courtesy of Kerry Frey, LMAC

system is perhaps the most impressive (Brown 1997, p.s4)." The F-22 is designed to simplify the role of the pilot by combining information from inside the aircraft with data from external sensors into a single display that provides a clear picture of the combat scene. Different portions of the avionics system (such as the radar, electronic warfare system, and CNI), as well as nearby F-22's, share extensive amounts of data. These data are processed and converted into useful output by two powerful common integrated processors (CIPs). This integrated avionics architecture represents a major departure from past federated architectures on previous fighters, such as the F-16. In a federated architecture, many of the sensors and systems work separately and have separate displays, requiring the pilot to manage each of them individually. This complicates the pilot's job, requires redundancy in equipment, and does not offer the same richness of integrated information. In contrast, an integrated architecture benefits from reductions in parts, weight, and volume. Figure 3.3 below shows a simplified comparison between integrated and modular architectures. Along with increased sharing of information across hardware, avionics architectures are trending towards increased digitization of functions and software complexity to achieve greater performance. These advances have been made possible by increases in both network speed and complexity (Pinney, 1994). In order to benefit from their many advantages, integrated architectures require greater integration among suppliers who develop and produce the various portions of the avionics system. Therefore, the F-22 program has faced a much greater challenge in coordinating suppliers' efforts and managing technological complexity across subsystems than previous programs like the F-16.

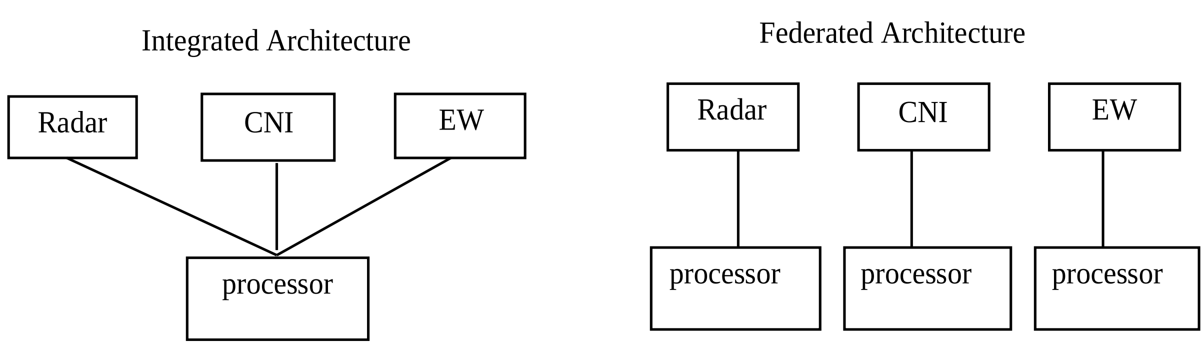

Figure 3.3 – Comparison of Integrated and Federated System Architectures

3.4 FORMS OF SUPPLIER INVOLVEMENT IN DESIGN AND MANUFACTURING

3.4.1 F-22 Approach

In an effort to ensure that F-22 designs both satisfied the needs of the final customer and incorporated early inputs from suppliers, the Air Force introduced the concept of “integrated product development (IPD)” in the early phases of the program. In order to implement IPD the program pioneered the use of integrated product teams (IPTs) in defense contracting, creating multi-disciplinary teams responsible for each of the plane’s major subsystems (e.g. avionics, propulsion, and airframe). These IPTs included a wide range of individuals from the contractor and the government organizations, such as material managers, engineers, supplier representatives, and acquisition personnel. This approach was successful at developing solutions that had the commitment of all the stakeholders involved. As a result of their effectiveness on the F-22 program, the use of IPTs has spread throughout the industry (Williams 1999, p. 132).

Industry personnel interviewed for this research project confirmed that the IPTs helped to facilitate earlier and closer involvement of suppliers in the development process. However, several of them also noted that a downside of the IPT process used on the F-22 was that frequent meetings consumed a considerable portion of their time, which tended to delay the process. Many program officials also believe that the demonstration/validation phase of the program was critical in creating an environment that motivated close collaboration between the contractor and suppliers. Before the government chose the winner of the ATF competition (later renamed the F-22), two industry teams competed to design and build test aircraft that demonstrated the performance capabilities defined during the earlier concept exploration and demonstration phase. This prototype process forced the teams to create early business and working arrangements that facilitated the multi-company cooperation necessary to build a successful plane (Williams 1999, p. 74-75).

3.4.2 F-16 Approach

In contrast with the F-22's design and development process, the F-16 program was much less team focused. The prime contractor (which was then General Dynamics) undertook a much greater portion of the design work. In many cases, suppliers simply received final drawings or sets of detailed requirements for manufacturing. Rather than being responsible for entire assemblies, supplier work was frequently limited to producing individual components, which the prime contractor then integrated. Relationships with suppliers tended to be more arms-length, with contracts going to the lowest bidders. One advantage of this type of suppler arrangement was that the prime had the ability to quickly make modifications to the design or adapt it to specialized customer requests. Changes required much less coordinated effort across the supplier network. For example, the F-16 contained a rack for the modular mission computer (MMC), which served as the central control for the avionics system. While the prime contractor outsourced the MMC, it built the rack and several of the internal circuit cards in-house. This was done because some of the rack's cards controlled the way the plane's bombs were dropped. The prime wished to both keep this knowledge proprietary and be able to easily reconfigure the card according to customer preferences for bomb dispersion.

The technology originally incorporated on the F-16 was much less complex than today's avionics. Therefore, it was feasible for the prime contractor to retain design capabilities and configuration control across the entire platform. With the increasing complexity of various subsystems and the specialized knowledge required to design them, however, it has become increasingly difficult for the prime to maintain a high level of competence in all areas. On the F-22, the company decided to identify and tap its suppliers' expertise in specific technologies. It would do so by farming out more of the design work to them. Correspondingly, closer collaboration and partnership with key suppliers became more critical in order to ensure design integrity. This trend towards greater dependence on suppliers continues today. There is increased emphasis within companies on narrowing their range of activities and outsourcing activities not considered to be core competencies.

3.4.3 JSF Approach

Lockheed Martin recently won a competition with Boeing to develop the next generation Joint Strike Fighter (JSF), which will eventually replace the F-16 as the multi-role fighter in the US Air Force, while also providing the Navy and the marines with the next generation fighter aircraft. While the F-22 design approach was characterized by integrated product teams and coordinated design, the JSF approach taken by Lockheed Martin features even greater outsourcing. Suppliers are being given full responsibilities for both designing and assembling entire aircraft systems. For example, rather than using separate suppliers for wheels, struts, and shocks, one supplier will be responsible for the complete JSF landing gear. Lockheed Martin hopes that this will lessen the prime contractor's burden of coordinating supplier activities and permit a greater focus on higher value-added tasks. In order to assume their larger roles, many suppliers will need to deepen their systems integration skills. Coupled with the current industry contraction, this increase in supplier responsibilities will likely result in fewer suppliers possessing much broader capabilities. Lockheed Martin will presumably become more dependent on and develop deeper commitments to those suppliers it has tapped to provide major assemblies and subsystems.

Early interviews signaled that for some critical items only two suppliers remained, one on the Boeing team and the other on the Lockheed Martin team. The implication of this was clear. Since the JSF will be the major defense aerospace program of the future, the outcome of the JSF competition could spell financial ruin for suppliers on the losing team. While this is far from being a foregone conclusion, it nevertheless appears to have cemented certain types of relationships prior to the outcome of the competition that are worth noting. Lockheed Martin personnel interviewed early in this research pointed out that cooperation between that company and its key subcontractors and suppliers have remained extremely high. In other industries, a company faced with growing dependence on a shrinking number of suppliers (i.e., Lockheed and Boeing) would likely cause managers and shareholders deep unrest. While it might be argued in certain instances that a few of the larger aerospace suppliers have gained considerable leverage at the expense of their prime contractors, those interviewed on the JSF program could not point to such a development with any degree of concern. Most JSF suppliers considered themselves part of a team locked in a fierce competition with very high stakes. Of course, the inevitable larger question is how suppliers on the winning team will behave after the dust has cleared and few, if any, suppliers with competing capabilities remain.

3.5 CHALLENGES OF TECHNOLOGICAL CHANGE

When the F-22 was being designed in the 1980's, the defense industry was much larger than today. The telecommunications and computer revolution was only beginning to accelerate. Defense contractors still drove demand for most advanced electronics components and wrote many of their technical standards. F-22 designers had good reason to believe that they were making smart technology decisions in their selection of processors, network interfaces, and microchips for the avionics. Unfortunately, as the program's EMD phase got underway in the 1990s, companies were caught off-guard by sharp cutbacks in defense funding, consolidation of the supplier base, and a revolution in the commercial electronics industry. Suddenly, manufacturers of RF devices, integrated circuits, and other critical avionics components turned to the larger commercial market. In turn, they began to lose interest in the declining defense business. The pace of technology quickened, with new chip designs emerging regularly to replace slower, outdated models. For example, the F-22 was originally designed using multi-chip modules (MCMs), which represented the leading edge in printed circuit board technology in the 1980s. However, they were soon replaced by new, application-specific integrated circuit (ASIC) technology and MCMs became extinct. Today, field programmable gate arrays (FPGA) are starting to replace ASICs. This exemplifies the challenge facing aerospace companies in keeping up with rapid technological change while designing products that require years to produce and remain in operation for decades afterward. While these technological innovations in microelectronics and telecommunications enable major advances in weapons system performance, they occur faster than the defense industry can integrate them into new designs and create difficult obsolescence problems. These problems were exacerbated on the F-22 by delays to the program resulting from funding uncertainty. The long time interval between design and production has increased the disconnect between the technologies employed in the original design and the technologies available today. As a result, the F-22 faces a severe problem with diminishing manufacturing sources (DMS), in which suppliers no longer produce certain electronics components necessary to manufacture the aircraft.

When compared to the F-16, in full-scale production throughout the 1980s and early 1990s, Lockheed Martin faces a very different contracting environment with the F-22. Managers at Lockheed Martin noted that they rarely experienced parts shortages on the F-16 (and often had the reverse problem of too much surplus inventory). They dealt with a supplier community that was eager for a share in defense programs. Competition for contracts was rarely a problem, as there were generally many potential suppliers possessing the required capabilities. Where there were few, they depended heavily on defense business for revenues. Another major difference between the two programs is the sheer volume of planes. Over 4,000 F-16s have been manufactured and sold to the US Air Force as well as to many foreign governments. Although current production rates are much lower than in the past, it continues to remain a popular fighter. In fact, the United Arab Emirates recently signed a contract worth up to $6.4 billion to purchase 80 new F-16s from Lockheed Martin, which will feature a redesigned avionics suite and improved radar (Fulghum, Morrocco, & Phillips 2000, p. 24). The F-16 was designed as a multi-role fighter and has been highly successful as a platform that has achieved longevity through many upgrades and design improvements. A well-designed, sturdy airframe coupled with a fairly easily modifiable internal architecture has enabled the F-16 to adapt to changing technology and remain a competitive and affordable platform.

The F-22, on the other hand, was designed with a more specialized mission (air-superiority fighter) and far more complex avionics. Projected production volumes are much smaller. One disadvantage of the plane’s integrated system architecture, for example in its avionics system, is that DMS problems can have far reaching consequences. Because functions have been integrated or combined where possible, a DMS component can affect several different subsystems. For instance, a change in interconnect technology would likely impact nearly all the sensors, which relay information to the central processor and to each other over a common network. F-22 designers also made decisions early on to use unique interfaces and components in order to create more commonality between avionics parts. The increased commonality was intended to reduce costs by increasing order quantities and facilitating easier maintenance. Unfortunately, this strategy backfired when commercial electronics began driving the technology market. The defense parts were unique and commercial demand for them was low. When they went out of production, the problem affected numerous portions of the avionics system. It would have been better to design individual parts according to the specific functionality required, using commercial parts and standards where possible. When parts went DMS, the problem could have been solved by upgrading to the next generation commercial part, or at least it would have been minimized by limiting it to a specific area and addressing it on an individual basis. This illustrates an important theme frequently discussed in the literature on design concerning the tradeoff between integrality for greater efficiency versus modularity for greater flexibility (e.g. Baldwin and Clark, 1999). In the case of the F-22, the selection of a highly integrated architecture proved very costly when the program was hit with many simultaneously occurring advances in underlying technologies. Companies should be on their guard about pursuing highly integrated architectures in cases where the embedded technology is moving rapidly in order to avoid falling into the same trap as the F-22.

3.6 LIMITED PRODUCTION SCALE

Low production volumes have also made it more difficult to attract supplier interest in the F-22 program. This leads to diminished competition for contracts, and consequently, less incentive for suppliers to innovate in order to win the business. When the EMD phase of the program began and government plans called for purchase of 750 tactical fighters, interest across the supplier community was higher than today. Due to soaring costs and budgets cutbacks, however, the projected future F-22 fleet now stands at 295 aircraft and some recent estimates have reduced this number even further. If cost overruns continue, cancellation of the entire program remains a possibility.

Because the F-22's performance is expected to exceed that of any other fighter aircraft on the world market, the US government is unlikely to approve wide spread sales to other countries any time soon. Therefore, the potential for additional business volume through foreign military sales is low. Yet, defense contractors generally reap their largest margins on foreign sales. In contrast, the US government, while funding the development of new technology, generally keeps a tight reign on the level of profit on domestic sales. However, contractors and their suppliers may be willing to accept low returns on US government contracts if they expect to later be able to sell the technology abroad for handsome returns. For example, the popularity of the F-16 on the world fighter-aircraft market has both benefited Lockheed Martin and helped to defray the plane's cost for its US customers. Since this is not the case for the F-22, suppliers are not greatly incentvized by the prospect of lucrative, future sales to foreign governments.

3.7 LESSONS LEARNED

One lesson the acquisition community learned from the F-22 and has applied to the JSF program is the importance of emphasizing affordability. This included recognizing the need for a reasonably high production volume to incentivize the defense community, provide manufacturers time to come down learning curves, and spread out fixed capital costs. Therefore, the JSF is being designed to fulfill the operational requirements of three services (Navy, Air Force, and Marines), with a high degree of commonality between the 3 design variants. In addition, the fighter will be sold to the United Kingdom's Royal Navy and Royal Air Force and potentially several other nations. The expected JSF flyaway cost ranges from $28 million (for the conventional take-off and landing version) to $38 million (for the carrier version), compared with an F-22 flyaway cost of approximately $80 million (Birkler, et al; 2001).

The JSF is also being designed for affordability through choice of technologies. Rather than following conventional defense contracting practices and opting for the most cutting-edge technology available, the teams have been encouraged to select designs which achieve good performance at a reasonable price. This might mean, for example, choosing a slightly slower processor already widely available on the commercial market rather than paying a premium for latest one to be developed. New technology should be demonstrated before decisions are made to incorporate it into the design. Designers have also sought to leverage proven, commercial off-the-shelf (COTS) technology wherever possible and plan-in future upgrades where technology is advancing rapidly. Experiences with the F-22 also taught the importance of designing according to commercial standards. This helps to decrease the chance of future DMS problem and ensure a future base of potential suppliers from which to procure material. For example, one area where this is especially critical is network technology, which provides the interconnection between major avionics systems and sensors. Commercial industry is currently developing new optical interfaces that will enable much faster rates of data transfer. Therefore, Lockheed Martin's JSF designers went to networking equipment manufacturers Nortel and Cisco to discuss technology directions. Unfortunately, these companies were not prepared to disclose their future plans at the current time. As a result, Lockheed Martin hopes to collaborate with BAE Systems and Northrop Grumman, two other major aerospace companies dependent on networking technology, to develop an industry standard. It is hoped that by making design decisions with an eye towards technology trends and lifetime supportability requirements, unexpected cost overruns can be avoided. The acquisition community has supported designers in containing costs by more carefully considering the performance requirements levied on contractors. While design margins on the F-22 were extremely narrow, they are more relaxed on the JSF, giving contractors more flexibility in making cost/performance tradeoffs. In turn, contractors have been able to pass on some of this flexibility to suppliers, giving them more room for innovation and avenues for cost minimization.

3.8 LIFETIME CONTRACTING

One way the F-22 and JSF programs might incentivize innovation where the F-16 program did not is through lifetime contracting agreements with suppliers. The F-16 has always undergone maintenance and major repairs at depots run by the Air Force. Therefore, manufacturers have historically had little stake in supporting the plane once it left the factory. The increasing complexity of technology, equipment, and personnel training required to repair more advanced aircraft, however, is making depot repair more difficult. A possible (and perhaps even necessary) remedy is to hand repair and maintenance responsibilities over to the suppliers who produced the systems and inherently possess the capabilities required to fix them. By signing lifetime support contracts, suppliers would be assured of future revenue streams on their products. This would provide additional incentive for suppliers to compete for contracts even when the volume was low. Assuming the repair agreements were structured properly, suppliers would also have a greater incentive to ensure the durability of their product. Of course, the danger is that if structured improperly, these contracts could actually reward poor initial quality by allowing suppliers to earn higher revenues the more repairs are required. With lifetime contracting, suppliers would be assured of receiving direct feedback when a design was faulty and gain insight into ways to improve future products. Interest among the supplier community in this type of contracting arrangement is reportedly high. While the Air Force has not yet decided exactly where and how maintenance and repair of the F-22 and JSF will be handled, it appears that lifetime contracting may be one promising approach.

4 INNOVATION ACROSS SUPPLIER NETWORKS

4.1 INTRODUCTION

This chapter reviews the major themes in the literature dealing with sources of innovation within and across firms. It focuses on determinants of innovation and the implications for companies seeking to encourage innovative behavior not only within their own facilities but across their entire supply chain. Innovation is addressed from the perspective of supplier relationships, considering methods by which firms build supply chains that incentivize and nurture creative behavior. Companies supported by innovative supplier bases often possess distinct competitive advantages relative to their competitors in the performance and cost of their products. Along with addressing the literature on this topic, this chapter advances a number of hypotheses concerning methods and incentive mechanisms by which customer companies might foster innovation across their supplier networks.

4.2 TYPES OF INNOVATION

Nearly every firm, whether explicitly or implicitly, seeks innovative ideas for creating both new and improved products and processes. As a result, researchers have extensively studied patterns of innovation and techniques for encouraging it. In order to partition this broad topic into more manageable categories, researchers often use terms such as “product”, “process”, “incremental”, and “radical” when describing innovation. Borrowing from Hall (1994 p.2), process innovation is defined as producing a given product in a new way, whereas product innovation is defined as altering a product or introducing a new product. Abernathy (1978) distinguishes between radical product innovation and incremental innovation. The former represents major shifts in a product’s design and generally occurs in the early phases of a product’s lifecycle, while the latter represents refinement of designs and production processes to reduce cost and improve quality and typically predominates in mature products. Figure 4.1 below shows these changes in the rate of different types of innovation over a product’s lifecycle.

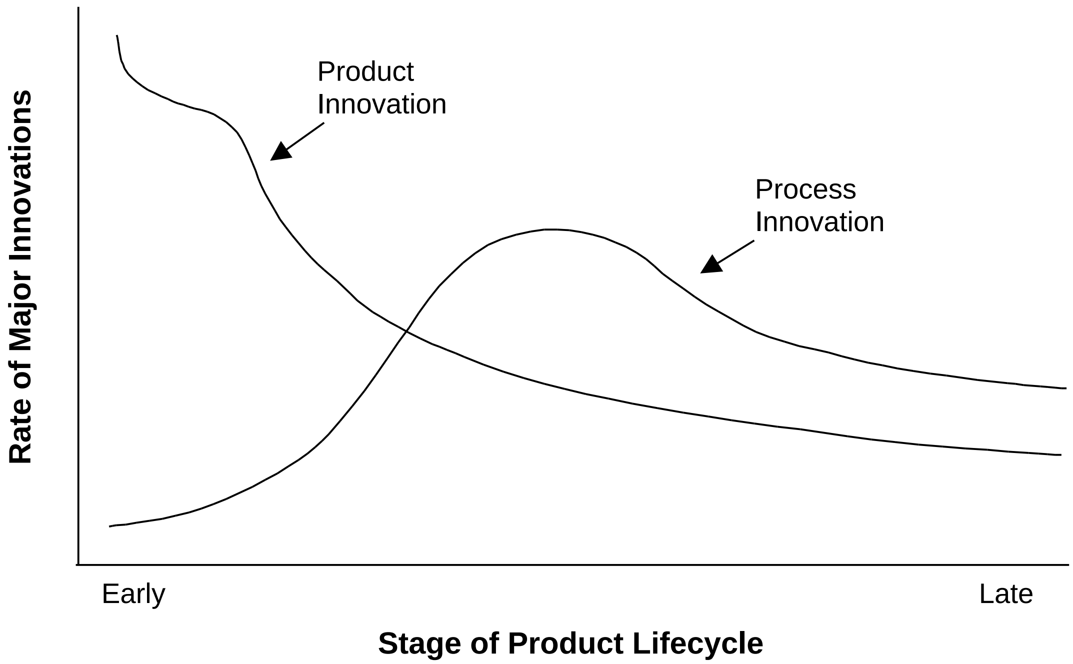

Figure 4.1 – Innovation and Product Lifecycle[4]

Henderson and Clark (1990) argue that delineating between incremental and radical innovation is insufficient and introduce two additional categories, architectural and modular. Modular innovation represents a major change in a core component of a design. In an avionics context, this might represent the replacement of an analog sensor with a digital sensor. Architectural innovation, on the other hand, describes a change in the interrelationship between core components. It can overturn the dominant design and may require new organizational structures within firms to incorporate the new knowledge. As a result, architectural innovation by competitors can pose a particularly dangerous threat to established firms, which often have difficulty recognizing and implementing the organizational changes required to compete under a new architectural paradigm. Henderson and Clark cite the development of the jet engine, which "would change the interaction between the engine and the rest of the plane in complex and subtle ways", as an example of a past unexpected architectural innovation.

[4] Based on W.J. Abernathy . ***The Productivity Dilemma.*** The Johns Hopkins University Press, Baltimore, 1978, p. 72.

4.3 INNOVATION IN THE DEFENSE AEROSPACE INDUSTRY

The defense aerospace industry possesses interesting and somewhat unique characteristics that differentiate it from other major industrial segments in the U.S. economy. It is a well-established industry with products that incorporate both mature and nascent technologies. While the basic airframe structures and overarching product system architectures have not changed considerably over the past 40 years, major changes in the embedded electronics technology are occurring very rapidly. While it may be argued that a dominant fighter platform design has emerged across the industry, this is not true of the avionics system. The military customer's continual demand for new, cutting-edge technology means that there has always been impetus for major product innovations that dramatically increase performance capabilities. These generally result from intensive R&D efforts and require lots of time to develop. A diminished defense budget and soaring costs, however, have placed increased emphasis on incremental product and process innovations that will improve affordability. Lavitt (1998) reports that aerospace companies are increasingly devoting scarce resources towards developing products and processes that have an immediate market impact while spending less on basic research. Competition among companies is increasingly based upon offering customers reliable performance at moderate prices rather than developing radical new technology. In contrast to the past, few major new defense programs have been launched over the past decade (Haggerty 2001)[5]. Rather, attention has shifted to extending the service life of older weapons platforms and producing current ones, like the F-22, at lower cost. Achieving these goals depends on participation and coordination of companies across the entire defense aerospace community rather than heroic efforts of a few major contractors. Therefore, this research primarily focuses on methods of fostering continuous product and process innovation across supplier networks, rather than on sources of radical product innovations, which occur less frequently and are often tied to major R&D endeavors by

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[5] Presentation by Allen Haggerty, "New Directions in the Aeronautical Industry," Massachusetts Institute of Technology, April 21, 2001.

individual firms. Of course, there are differences between aerospace prime contractors and lower-tier suppliers in the types innovation they tend to produce. The primes have a much larger role in defining the design of new weapons systems and are, therefore, more likely sources of architectural innovations. Suppliers, on the other hand, are typically responsible for specific subsystems or components outsourced to them by the primes, making them more likely sources for incremental and modular innovation.

4.4 FOCUS ON THE SUPPLY CHAIN AS SOURCE OF INNOVATION

The literature on innovation commonly suggests a range of methods and strategies for firms to adopt in order to encourage innovative behavior. Woodman, Sawyer, and Griffen (1993), for example, emphasize the importance of organizational culture, rewards, and resources for fostering creative behavior. Urabe (1988) argues that a cooperative relationship between management and labor is a crucial factor in promoting process innovation. Thomke (2001) recommends a system of rapid experimentation, where the value of new ideas can be tested quickly and cheaply. The literature says little, however, about incentivizing innovation across a firm’s suppliers. In the traditional arms-length approach to supplier relations, firms have simply assumed that this is the responsibility of the supplier’s management team. Competitive market pressures would be sufficient to ensure that supplier develop innovative new products and processes. As the lean revolution has swept U.S. industries, however, there has been a growing recognition of suppliers as strategic partners and key members of the extended enterprise.

Major aerospace firms that have begun to see the benefits of implementing lean practices in their own facilities are now realizing the additional value that can be created by collaborating with their suppliers. Due to the size and complexity of aerospace products, suppliers play a major role in contributing knowledge and expertise to the final assemblers. A large portion of final product cost resides in the supplier base. With consolidation of the industry that has occurred in recent years, dependence on key suppliers that remain has increased. In many cases, only one or two firms remain in the industry which possess certain critical manufacturing capabilities. As a result, sole-sourcing relati onships are fairly common and the threat of competition is less likely to be a strong motivator of innovation, particularly in the high-risk defense aerospace environment. However, partnerships with suppliers hold the promise of facilitating complex coordination that guides a supplier's creative activities in directions most beneficial to the customer and results in gains for both parties. Teece (1992) presents a strong case for such strategic alliances between firms, arguing that they are valuable mechanisms for supporting innovation. In his study of the semiconductor industry, Kimura (1997) concludes that Japanese firms succeeded due to their horizontally diversified, vertically integrated firm structure. Through sharing complementary assets, they were able to outperform U.S. firms, which were typically independent, single-product companies. Many of the major aerospace contractors have recognized the importance of supplier participation in lean manufacturing to the extent that they have demanded just-in-time deliveries to their own factory floors and have trained suppliers to implement quality procedures. However, they have just begun to go beyond these basic lean practices and ask how they can build highly innovative supplier networks. They are increasingly realizing ways in which they can become much more competitive by finding ways to assist and reward suppliers in generating creative new product and process improvements – innovations that help to drive down costs, improve quality, reduce cycle time, and enhance product performance.

4.5 IDENTIFYING SPHERES OF INFLUENCE

Deciding to pursue greater innovation across the supply network through cooperation is only the first step. Firms must wisely employ a differentiated strategy in extending their hand to suppliers. In light of limited resources, they should focus their efforts on those suppliers with the greatest strategic importance rather than attempting to help all suppliers indiscriminately. When the item being procured is not highly specific to the customer's product and a broad supply base exists, market-based solutions are often best. This is actually characteristic of Japanese lean manufacturers, which strategically segment their supply chain and pursue both arms-length and partnership relationships, depending on the nature of the component being procured (Dyer, et al. 1996). Outsourcing greater integration responsibilities and reducing the number of sources also enables firms to develop deeper relationships with the remaining key suppliers. Bakos and Brynjolfsson (1993) present economic models to show that even in the presence of reduced coordination costs (due, for example, to information technology), firms can often maximize profits by relying on fewer sources. This reduces their bargaining power but increases the incentive for supplier investment in noncontractible investments that yield valuable paybacks.

In designing a strategy for supplier relationships, however, it is important for the customer company to consider not only its dependence on the supplier, but also the supplier's dependence on it. In a study by Kamath and Liker (1990) of innovation across suppliers in the automotive industry, they find that independent suppliers are primarily motivated to pursue innovation when opportunity for reward outweighs the cost. Dependent suppliers, however, can often be motivated to innovate in the absence of clearly favorable conditions if they have a good understanding of the types of innovations that the customer values. Dependence, for suppliers, typically means the degree to which a supplier relies on the business of a customer for its revenue stream. It is also often a function of the extent of strategic learning derived from the relationship. For the customer company, dependence refers to reliance on the supplier for unique knowledge or capabilities critical to the customer's product. It usually is a function of the essentiality of the procured item to product performance and the availability of alternative sources. Both aspects of customer-supplier dependence play a role in determining the type of relationship that will create the greatest long-term value for the customer.

4.6 INNOVATION ENABLERS AND INCENTIVES

Once they have conducted a strategic assessment of their supplier networks, firms must determine how best to proceed to stimulate supplier innovation. The ultimate goal is to maximize expected innovation benefits ensuing from investments in collaboration and direct limited resources towards strategies with the greatest potential for creating value. This thesis explores the various innovation enablers and incentives a customer might pursue with its suppliers. It seeks to provide insight into the nature and potential benefits of the various levers by which a customer might drive innovative activity by its suppliers. The primary levers explored in this thesis, based on ideas that emerge from the literature on innovation and supplier relationships, are communication, training, shared investment, and contract structure. This thesis also considers potential barriers to greater innovation and suggests ways contracts might be restructured to overcome some of them.

4.6.1 Communication

The literature reveals that good communication between the customer and supplier is an important facilitator of innovation. It both helps to reduce supplier uncertainty and permits the exchange of ideas between the two parties. Inter-organizational communication allows the customer and supplier to pool knowledge and experience to solve problems jointly. The benefits of collaboration are often mutual. The customer gains a better understanding of the supplier's capabilities and constraints, and can select designs that minimize cost for a given performance level. The supplier gains a clearer perspective of the customer's requirements and insight into what it most values. This enables suppliers to suggest solutions that maximize customer satisfaction. It also gives the supplier guidance in making competency-enhancing investments that aid its strategic positioning for future business.

Von Hippel (1982) argues that understanding the "user's needs" should be a central part of a manufacturer's innovation strategy. A product's user is most aware of his needs and often develops innovative solutions to fill them. The user may initially provide a solution himself because the need is urgent and the manufacturer may be unwilling to engage in an uncertain market. Suppliers should develop mechanisms to capture and build on these needs and innovative ideas of their customers. In fact, studies suggest that innovative organizations receive between 34% and 65% of their critical input leading to successful innovations from external sources (Conway, 1995). Research by Kivimaeki, et al. (2000) focusing on small and medium-sized industrial enterprises shows a link between a firm's interaction with clients and other firms and the number of patents originating in that organization. Although the number of patents does not provide a direct measurement of innovative activity, it is commonly used in studies as an indicator of innovative output. This literature suggests the importance of information exchange that originates not just from the prime contractor, but also from a careful analysis of the warfigther's needs. Good communication flow along the entire path from the warfighter to the Systems Program Office (SPO) to the prime contractor to suppliers can be an important stimulant of supplier innovation. Of course, this path has traditionally been rife with barriers to information flow, obscuring the understanding of the real needs of the user. For example, studies indicate that System Program Offices (the prime's customer) have sometimes failed to adequately represent demands that the soldier or pilot in the field considers essential (e.g., Nuffort, 2001).

A supplier will generally be more likely to invest resources and expend effort to pursue innovation when the buyer's technological targets are better defined. Suppliers realize that customer companies that understand the purpose of their innovative activities will be more likely to be receptive to the results (Kamath & Liker, 1990). Communication softens resistance to new ideas and helps to avoid the not-invented-here syndrome, in which the customer's engineers are prone to reject all ideas that originate outside their company. The need to educate the customer company on the nature and advantages of products is echoed by Athaide and Stump (1999), although they astutely point out that there are several potential risks. One is that the customer company may steal the innovation for itself. The other is that by requesting excessive modifications, the customer will cause specification creep that slows down the development process. In order to encourage suppliers to be forthcoming with innovative ideas, the customer company should seek to allay such potential concerns. The customer should encourage openness among its employees to new ideas from outside the organization and promote careful consideration and experimentation with solutions suppliers may offer.

Better communication can also lead to greater trust. When companies trust one another they are able to eliminate costly mechanisms for protection and share more useful information, increasing the efficiency and value in their interactions. This can become a positive, self-reinforcing, process in which communication increases trust, which further increases communication. Research on U.S., Japanese, and Korean automakers finds that where high levels of trust exist in the supplier relationship, the automaker spends significantly less time discussing unproductive, transaction-oriented issues (Landry 1998a). It is found in this research that purchasing agents are more efficient, handling on average more than twice the dollar volume of goods, and suppliers and customers are far more likely to exchange suggestions on ways their partners could improve their processes. Research by Zaheer, McEvily, & Perrone (1998) also demonstrates a positive correlation between interorganizational trust and supplier performance. Rather than simply pursuing greater data exchange with its suppliers, the literature suggests that firms should strive for communication that builds trust.

4.6.1.1 Forms of Communication

Communication can take many forms and the effectiveness of various methods will vary according to the type of relationship. One objective of this research is to determine which forms of communication have been most successful in stimulating innovation in a range of typical relationships within the defense aerospace context. Ultimately, one would like to develop a mapping between recommended communication methods and relationship characteristics. One type of buyer-supplier interaction that has become more frequent in the U.S. automotive and aerospace industries is the use of integrated product teams (IPTs), a practice learned from Japanese lean manufacturers. IPTs involve the creation of cross-functional teams, facilitating increased communication across departments within a company (e.g. purchasing, engineering, and manufacturing) during the product develop process. They also frequently include members from major suppliers. In the defense industry, these teams sometimes include acquisition personnel who are supposed to help ensure the satisfaction of the end user (although this has not always been as effective as desired). IPTs have helped companies to take into account the capabilities of suppliers when making critical design choices and to reduce costly and time consuming engineering design changes (Bozdogan, et al. 1998; Hsu, 1999). Takeishi (2001) finds that in the automotive industry both early integrated problem-solving and frequent face-to-face communication between buyer and supplier correlate with better component design quality. This lends support to an hypothesis of this research that closer communication resulting from the use of IPTs fosters innovative ideas relating to product design and improvements. This idea will be further explored in the case studies.

Communication can also occur through collocation of customer company personnel at supplier facilities. This is another strategy commonly employed by Japanese auto companies. These personnel often assist the supplier in design, production, and inspection and provide suggestions for potential improvements. Through this process, the buyer’s engineers become more familiar with the suppliers capabilities and methods. In an extreme form of collocation, Japanese companies even engage in inter-firm employee transfers, in which employees work for extended time periods for partner companies (Dyer & Ouchi 1993, Nishiguchi 1984). This not only broadens engineers’ experience, but leads to a cross-pollination of ideas across firm boundaries.

A good information technology infrastructure can also improve interfirm communication, enabling frequent exchange of data. New computer-aided design programs make possible real-time input into design decisions from remote locations and enable rapid design iterations. Enterprise resource planning (ERP) and manufacturing resource planning (MRP) systems enable tighter coordination of delivery schedules and production planning. E-mail, teleconferencing, and the worldwide web have also become valuable avenues for communication. A strong digital connection with suppliers appears to be an important enabler of innovation-rich communication.

Other informal means of communication can also be important for innovation, particularly if they build trust. These might include events where members from two organizations get together to socialize or participate in team-building activities. It might include conferences to discuss new technologies and strategies. It should also be noted that both supplier-buyer exchange and supplier-supplier communication are important. For this reason, Japanese companies often encourage their suppliers, including direct competitors, to meet together and share ideas. For example, Toyota has three regional supplier associations consisting of first-tier suppliers that meet to discuss findings on better ways to make parts. Most Japanese automakers also have associations for second-tier suppliers as well. These associations have served an important role in the past in disseminating new manufacturing techniques such as statistical process control (SPC) and computer-aided design (CAD) (Womack, Jones, & Roos, 1991).

Hargadon and Sutton (1997) argue that innovation results from capturing and building on old ideas to create new ones, something they refer to as “knowledge brokering”. Ideas come from a wide range of sources, and companies should establish methods to systematically identify, preserve, and share them. One way this can be done is through what Allen (1966) calls “technological gatekeepers”. These individuals scan corporate research centers, supplier networks, customers, and other industries for new technologies and ideas that may be applied to their company’s products or manufacturing processes. They continually infuse the company with new knowledge drawn from outside sources. Furthermore, they share this new knowledge with strategic suppliers and customers that would benefit from it. The ultimate goal is to have a steady stream of innovative ideas flowing into the firm and being passed on to strategic partners, enriching the network with knowledge and creativity. “Technological gatekeepers” may include internal consulting groups, individuals with extensive industry experience who float between a wide range of projects, or traveling liaisons who routinely visit partner sites. Few studies have focused on the functioning of gatekeepers and their effectiveness in diffusing innovation. Nochur and Allen (1992) suggest that simply establishing and assigning the job title is insufficient. Organizations should identify individuals who already fill the gatekeeper role in an unofficial manner and give them positions in which they can use their technological and communication skills to maximum benefit. This study will further probe this issue and consider how gatekeepers might effectively be employed in the aerospace industry.

4.6.2 Training

Japanese manufacturers are well known for providing training to their suppliers. This often involves sending lean deployment teams to supplier factories. These teams help to identify areas of waste and inefficiency within the supplier organization. They recommend process improvements, and suggest ways to rearrange the factory floor to reduce inventory, create single piece flow, reduce cycle times, and improve quality. Many major US companies, including those in the aerospace industry, have begun adopting these suppler training practices. In addition to having these traveling “lean teams”, many of these companies hold regular supplier workshops, in which they educate suppliers on best manufacturing practices, teach design for manufacturability and quality control techniques, and share success stories. The purpose of all this training is to help suppliers improve their production processes, reduce costs, and improve their quality and delivery times. In the course of implementing these improvements suggested by the customer, it is hoped that “lean champions” will emerge within the supplier organizations. These individuals will internalize the lessons learned from training and will continue applying them across the supplier company, finding innovative new ways to improve a wide range of its products and processes. Training also demonstrates a clear commitment to the supplier. It indicates that the buyer has a sincere interest in the supplier’s success and intends to support that supplier and remain a loyal customer. This generally results in a reciprocal commitment on the part of the supplier, accompanied by a willingness to take risks and make extra efforts to please the customer. The buyer’s support not only indicates that innovation is important but also helps to ensure that it occurs. Of course, this implicitly assumes that the supplier is somewhat dependent on the buyer, values its business, and is willing to accept its suggestions.

4.6.3 Investments

A buyer can also demonstrate commitment and encourage innovation by helping suppliers make investments. These include asset-specific investments made by customer companies that are specific to the relationship with a particular supplier firm and which the supplier firm cannot use to benefit its other customers. As Hall (1994, p.56) mentions, investment in new capital is nearly always a prerequisite for technological progress. One can expect that even if generating innovative ideas themselves is not always costly (since innovative ideas originate from more than just making extensive R&D investments), there will often be a non-negligible expense to implement them. Investments in suppliers may include such things as sharing in the cost of machine tools or equipment that will improve production processes and reduce cost over time. It may also mean shouldering expenses for product redesign to reduce manufacturing costs or improve performance. In Japanese manufacturing industries, companies commonly support supplier R&D efforts towards developing new technologies (Goto 1997). Such investments help suppliers to develop new capabilities and skills that will ultimately benefit their customer in the form of improved products at lower costs.

The rate of return on many investments is uncertain, particularly in cases where future customer demand is unpredictable. Therefore, suppliers may be unwilling to make them on their own. By sharing part of the risk, the buyer can soften the potentially detrimental impact of investments that may perform poorly. Even when the payoff is relatively certain, the payoff period may be several years. Without assurance of long-term demand from the buyer, suppliers may fear being unable to recoup their investment. In some cases, suppliers simply lack access to sufficient capital pools to pursue innovative activities or fund investments in new ideas that would clearly be beneficial. In describing a resource-based view of innovativeness, which especially applies to smaller firms, Hadjimanolis (2000, p.263) states, “One of the main problems that such firms face in innovation is the relative lack of resources and the need to obtain them through collaboration with other firms or organizations.” Here, the buyer can help. By supporting the supplier in these initiatives, the buyer expects to receive some portion of any realized cost savings and experience performance gains in the product it procures. This requires establishing creative, up-front mechanisms for settling on an appropriate price and profit sharing arrangement. In cases of jointly funded research or shared investment in highly specific assets, companies also need to be cognizant of potential intellectual property rights and ownership issues. These considerations can make supplier investment decisions more difficult. Nevertheless, sharing in suppliers' investment expenses can encourage them to put forth the extra resources and effort required to achieve innovative new solutions.

4.6.4 Contract Structure

Buyers can also incentivize innovative behavior through the structure of their contracts with suppliers. Here the buyer faces a number of options regarding contract terms, contract length, and number of sources. A variety of factors must be taken into account in determining the optimal contract structure for each supplier relationship. These include the degree of competition, the knowledge content and technological maturity of the item, the rate of technological change, and transaction costs. The more competitive the environment surrounding the item to be procured, the greater will be the drive to innovate, generally speaking, among suppliers. In cases of intense competition, the nature of supplier relationships may be inconsequential compared to market forces in driving innovation. As mentioned previously, however, it may also be advantageous to intentionally limit competition by committing to a select number of sources, which can improve coordination and encourage investment in noncontractual assets. In the case of technologically mature items with minimal new knowledge content, room for innovation may be small and an arms-length, competitive approach may be best. In the reverse case, choosing a few key suppliers is often better. With increasing rates of technological change, maintaining multiple suppliers helps to ensure maximum exposure to the next breakthrough, from whatever source it may come. On the other hand, transaction costs can be reduced by minimizing the number of sources, keeping the contract terms simple, and avoiding frequent negotiations. The buyer should carefully consider the exogenous variables described above before making decisions regarding the contract variables within his control.

One potential means of encouraging innovation is through long-term contracts with suppliers. Rather than renegotiating prices and requirements frequently (e.g. yearly), they can be agreed upon for several years in advance. This ensures the supplier a predictable demand, which incentivizes it to invest in innovative ideas and pursue new ones even though they may have a lengthy payoff period. Through experience gained producing the item and working with the customer, the supplier will also be more likely to discover better processes and design improvements. Although the buyer might not experience the cost reductions associated with innovation immediately (due to the long-term nature of the contract), the price following renegotiation at a predetermined future date may be much lower than if the innovations had never occurred because of a contract that only encouraged a short-term focus. On the other hand, long-term contracts may reduce the incentive to innovate that competition provides. They may also lock the buyer into a particular supplier and design. To counter these negative affects, Japanese companies often engage in long-term commitments but source an item from two or three suppliers. This provides competition and flexibility, along with partnership, because the percentage of the total contract each supplier receives varies with its performance. In addition, the leading supplier is required to help train the lagging one(s) so that they share and build on each other’s innovative ideas (Richardson, 1993). In the aerospace industry, however, duel-sourcing is often not a viable option. Due to component complexity, specialization, and low volume, it may not be economically feasible to have more than one supplier. Even the threat of replacement down the road may be small, since there are sometimes few alternative sources possessing the necessary capabilities, and switching costs would be high. When alternative sources do exist, suppliers would presumably agree to more ambitious cost or performance curves in exchange for being designated as the sole source for several years forward. When a supplier is the only available source, however, it is virtually already assured of future business. Therefore, concern about reducing competition or locking into one design as a result of long-term contracts with that supplier is beside the point. A longer-term contract would essentially just involve reaching an agreement on prices for several years in advance rather than on a more frequent basis. Both parties could benefit from this arrangement. The supplier would be incentivized to innovate through the potential surplus to be derived over multiple years by reducing costs below the target price. In exchange, the customer would expect to receive a much lower price upon eventual contract renegotiation, as shown in Figure 4.2 below. However, this assumes the customer is able to closely observe the supplier's cost structure and credibly demand a price reduction based on the supplier's past performance. This thesis investigates whether this logic actually holds true and whether long-term contracts have the potential to spur greater innovation in a cost effective manner.

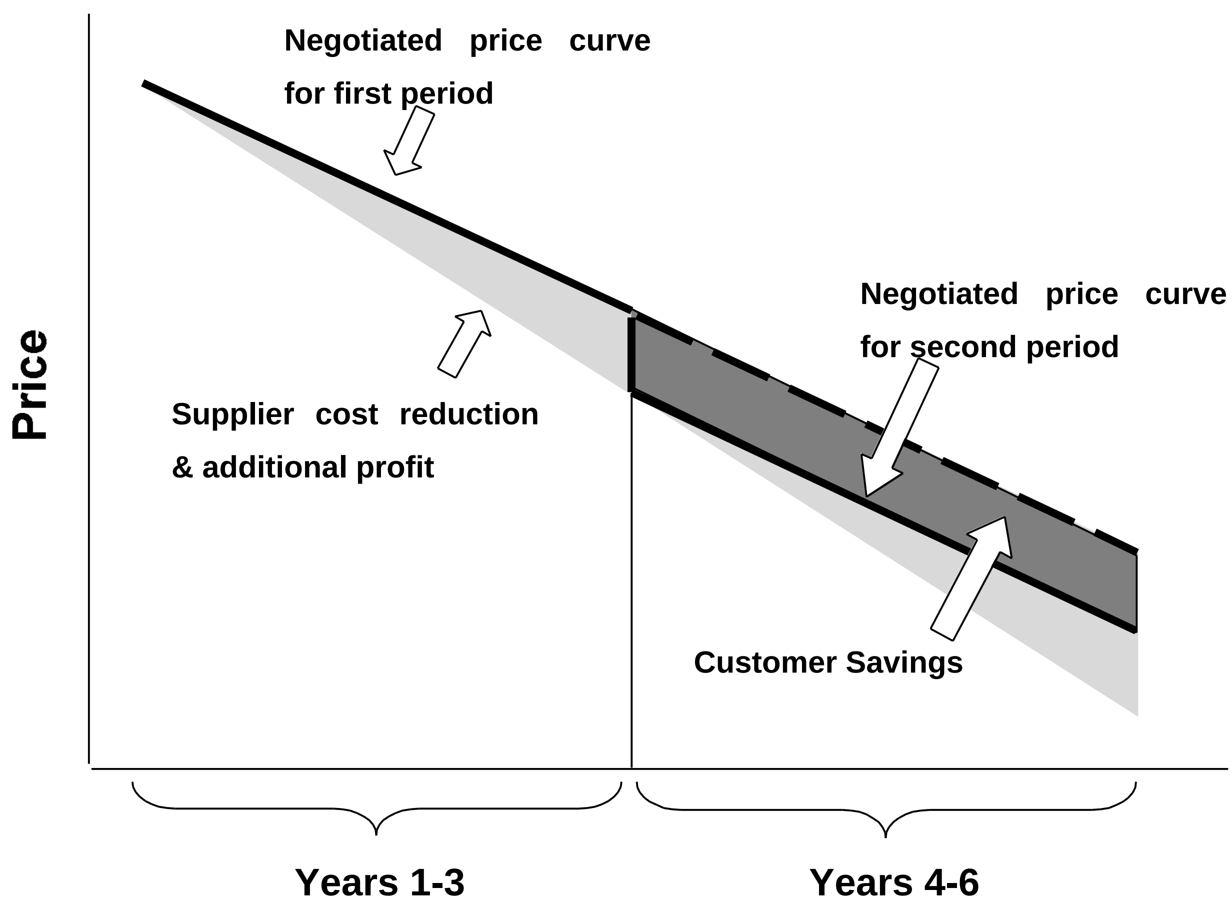

Figure 4.2 – Long-term Contracts and Pricing

The most direct means of incentivizing innovation is to tie clear financial benefits to innovative behavior through the contract terms. The research explores creative ways aerospace companies might write their contracts to do this. In a detailed study describing how Chrysler transformed its supply chain into an “American keiretsu”, Dyer (1996) argues that the key to transforming suppliers into true partners is establishing means to incentivize suppliers to participate in “expanding the pie”. A key step for Chrysler in demonstrating its commitment to suppliers was showing a willingness to share gains with them. Of course, sharing gains requires a profit-sharing system that rewards suppliers according to improvements in performance and reductions in cost achieved as a result of their innovations. For example, Button & Holt (2000) suggest that each link in the supply chain could agree to accept some percentage of the final product’s selling price, rather than charging a fixed cost for their components at sale to the next link in the chain. In Japan, companies often employ a “target costing” system. Target costing involves setting cost goals for components based on the expected final value of the product and then sharing gains when suppliers reduce costs below the goal. This is effectively a profit-sharing system to reward suppliers for innovation and improvement (Landry 1998b). However, it requires having sufficient insight into suppliers’ cost structures to determine whether savings are being accurately reported. Another possibility is to sign lifetime supportability contracts with suppliers. For preset fees, the supplier agrees to support and repair its product for life. This might include a fixed warranty fee for defective items and standard repair charges for damaged items. Such maintenance, repair, and overhaul (MRO) contracts incentivize the supplier to design products well the first time to minimize repair expenses. It also ensures feedback on poor-performing products, which will help to improve future products. The commercial aircraft industry is increasingly adopting such contracts, particularly the largest OEMs. The question of its feasibility within the defense sector remains open, something this study will explore further.

In the defense aerospace industry, a number of contract varieties exist and can impact the nature of the program. However, the two simplest and most common types are fixed-price and cost-plus contracts. In the former, the buyer negotiates a firm price at which it will procure the item. In the latter, the supplier receives some fixed percentage profit on top of its reported cost for producing the item. Fixed price contracts generally provide greater incentive for innovation from the standpoint that suppliers can make additional profits by reducing costs. Nevertheless, cost-plus contracts have other advantages and are also used frequently, particularly in design and development phases of projects. Due to the uncertainty involved with developing complex new technology, suppliers under fixed price contracts may charge extremely high prices to compensate for the risk. They would also be prone to choose the least risk technology solutions, rather than pursue innovative new possibilities. Therefore, the buyer may opt for cost-plus contracts coupled with close monitoring of the suppliers' costs. Deciding which contract type to use can sometimes be difficult, particularly as a program transitions from design and development to early stage manufacturing. This research explores the pros and cons of each approach during this phase of the F-22 program.

4.7 DISTINGUISHING CHARACTERISTICS OF THE DEFENSE AEROSPACE INDUSTRY

This section examines the unique characteristics of the defense aerospace industry and how they impact the methods described above for incentivizing supplier innovation. Although researchers have extensively studied many aspects of supplier relationships, few of them have focused on the aerospace industry. This is mostly likely due to the fact that data are hard to collect and the industry's peculiarities make generalization of results difficult. A firm understanding of the often complex defense environment is required before hypotheses can be posed. The primary feature that sets the defense aerospace industry apart from the commercial sector is the nature of its primary customer, the U.S. military. Government funding practices and special military requirements have a significant effect on the behavior of firms in the defense sector. These often present barriers to innovation rather than encouraging it.

4.7.1 Technology Challenges

The defense aerospace industry relies on complex and sophisticated technology. In order to meet the military's demand for the most advanced weapons in the world, companies are often pushing the technology envelope in producing their products. As a result, the process involves both high risks and high expenses. The military customer, faced with a limited pool of funding, has two conflicting objectives that it must balance. On the one hand, it would like encourage innovation and the development of new technologies that will ensure competitive advantage on the battlefield. On the other hand, it also values the lower risk and proven performance of more mature technologies. Unfortunately, its tradeoff or preference function between these two objectives is often unclear to the manufacturer (and perhaps even to the customer itself). This leaves the manufacturer and its supply chain uncertain about the intensity with which it should pursue each goal.

Defense products generally have very specialized applications and requirements, and potential customers besides the US government are few. Most products must meet demanding military specifications (mil-specs) to ensure reliable operation in extreme, rugged environments. For example, many of the chips used in avionics applications must function in temperatures ranging from about –55 degrees to +125 degrees Celsius. The same chips used in commercial applications are only designed for temperatures between about 0 and 70 degrees Celsius, or at most –40 to 85 degrees Celsius for industrial applications (Mullins, 2000). Therefore, military chips require specialized design and manufacturing techniques, and must undergo expensive qualification procedures to ensure that they meet specifications. In addition, many defense products have no commercial applications. Coupled with the low production volumes characteristic of the industry, the market only supports a limited number of suppliers in each defense product category. This decreases sourcing options and limits competition. For many items, such as small electronic components, suppliers have found the commercial world far more profitable and become disinterested in defense business. Because defense business represents only a fraction of such suppliers' revenues, incentivizing innovative behavior is particularly difficult. The military has taken some steps to eliminate unnecessary mil-specs and allow greater use of commercial-off-the-shelf technology (COTS) to reduce costs and increase access to commercial advances, but this will not eliminate these problems completely.

The complexity of the technology often makes the development of more than one source too costly. When the EMD phase for an avionics subsystem costs several million dollars, competing it among several suppliers, only one of which will win the contract, is often impractical. Splitting the contract among more than one of them would likewise be difficult. The coordination costs and capital intensity would be too great for the level of production volume. Once the buyer has selected a supplier, the switching costs also tend to be very high for complex aerospace products. Technological lock-in occurs because the supplier's product is specially designed to integrate into a complicated system with a unique set of interconnects. Another supplier cannot quickly replicate such a design and seamlessly plug its product into the existing configuration. Losing a competition for a new contract often locks a company out of all future business on a particular program. It can also put it at a disadvantage in future competitions held by the buyer for other contracts. When this occurs across several programs, it can lead to a loss of key capabilities in the supplier base and further reduction in competition.

The government organizes defense funding into programs. Programs generally represent large projects to develop, produce, and maintain a particular weapon, such as the F-16 or F-22. Major programs such as these frequently run in the billions of dollars and may last for 20-plus years. During the initial design and development phase, the prime contractor defines the product architecture and (along with the major suppliers) performs a majority of the research necessary to create the desired performance capabilities. The prime contractor also selects its major suppliers (which in turn select their suppliers) during this phase, many of which will retain this position for the life of the program. Technological refreshes and design upgrades take place as the program matures. Any significant design innovations, however, must occur early on in the program. Afterwards, the architecture remains fixed and incremental process and product innovations become the primary source of performance and cost improvements. Because the production and maintenance phases of most major programs are much longer than the design and development phase, a special interest exists in stimulating these types of innovations.

4.7.2 Funding Obstacles

The instability and bureaucracy associated with government funding often presents a major obstacle to innovation. Funding decisions for major programs come from the US Congress and are generally made on a yearly basis. This complicates long-term planning because the future availability of funds depends on the political climate in Washington in upcoming years, which tends to be very unpredictable. Buyers have difficulty concluding long-term contracts with their suppliers when demand is unpredictable. Suppliers may hesitate to make investments with long payoff periods for fear that orders for their product will suddenly cease. They may be unwilling to search for or implement improvements to their products or processes that do not yield results immediately. Funding uncertainty lends a short-term focus to activities across the entire defense aerospace industry. The effect of this demand volatility is magnified as one goes down the supply chain from the prime contractor, a phenomenon Fine (1998) refers to as the “bullwhip effect”. As a result, the uncertainty can create a strong disincentive for innovation among suppliers.

Mandated accounting practices and regulations on profit also discourage innovation. The acquisition community has increasingly tried to use fixed-price contracts to incentivize cost reduction activities and eliminate the monitoring bureaucracy associated with cost-plus contracts. Nevertheless, the government often imposes rules that restrict suppliers’ ability to benefit from savings initiatives. For example, the contracts are often renegotiated yearly and any reductions in cost the supplier realized in the previous year are subtracted from the price in the upcoming year. This prevents the supplier from realizing the full benefits of cost savings beyond the first year in which it makes an investment. Government imposed Cost Accounting Standards (CAS) effectively require suppliers to fully reveal their cost structures to enable the customer to limit “excessive” profit. While this prevents price gouging by the supplier, it may also discourage investment decisions that would ultimately benefit both the supplier and the customer. Defense Federal Acquisition Regulations (DFAR) and Defense Federal Acquisition

Regulations Supplement (DFARS) dictate to prime contractors the type of contract they may sign with suppliers rather than providing them the freedom to choose the terms they feel would be most effective.

Another aspect of the defense environment that hampers long-term, fixed-price contracting is the uncertainty of technology and cost. Most programs have a long duration, yet much of the embedded technology changes rapidly. Therefore, suppliers face uncertainty not only in the cost of developing cutting-edge products but also in producing them over time. They cannot easily anticipate the direction of technology and how this might affect the architecture of their product. Components or subsystems may change dramatically due to technological advances or shifts in commercial standards. Many of the original components may go out of production, requiring the development of expensive specialized suppliers to continue producing them or requiring a costly redesign of the product. In some cases where a company faces diminishing manufacturing source (DMS) problems, it may be able to remedy them affordably with an advance buy. When the future demand of its customer is uncertain, however, the supplier will be reluctant to risk making a large up-front payment for items it may never need. This is another problem caused by the defense funding process. In any case, suppliers cannot accurately forecast the shape of their cost curves for several years in advance. If they guess correctly in choosing the technology on which to base their design, costs could decline rapidly as the technology becomes more common. If they choose wrongly, costs could soar. As a result of CAS and DFAR's, long-term, fixed price contracts may expose the supplier to high downside risk if costs increase, but minimize upside potential by limiting allowable profits. Short-term contracts, however, reduce suppliers' incentive to consider the long-term implications of their design decisions. They have less interest in identifying and managing potential DMS problems early, before they become costly.

4.8 CHAPTER SUMMARY

Based on a review of the literature, this chapter set forth four central hypotheses regarding practices through which customer companies can foster greater innovation across their supplier networks. The case studies reported in the subsequent chapters seek to explore the extent to which 1) good two-way communication between the customer company and suppliers, 2) various forms of supplier training provided by the customer, 3) joint funding of supplier investments, and 4) incentive mechanisms built into contracts are important drivers and enablers of supplier innovation. Innovations can be classified into a number of different categories, and different types of innovation tend to predominate depending on industry environment, product maturity, and a variety of other factors. In studying innovation in the context of customer-supplier interfaces in the aerospace industry, this research concentrates primarily on product and process innovations (e.g., encompassing incremental, modular and architectural innovations) in the context of product design and development. Unique characteristics of the defense aerospace industry color the nature of relationships between companies, influencing their behavior and the dynamics of innovation. In some cases, this may present special challenges and necessitate nuanced approaches to fostering innovation through supplier relationships.

5 CASE STUDY A – F-22 RADAR

5.1 BACKGROUND AND INTRODUCTION

In 1991 Aerospace Technologies Corporation (then National Electronics Group), as part of a joint venture with another major defense contractor, won the contract to develop the AN/APG-77 radar for the F-22. This was the first active, electronically-scanned aperture radar planned for production. The APG-77 featured a revolutionary new system architecture and is probably still the most advanced airborne radar in the world. Rather than a conventional mechanically gimbaled antenna, its antenna consists of hundreds of small, individual transmit and receive modules and radiating elements which are smoothly integrated into the plane's surfaces. This gives the plane a low radar cross section to support its stealthy design. Solid-state microwave modules have replaced traditional traveling wave tubes and are expected to significantly increase reliability and transmission bandwidth. The radar is also designed with agile beam steering, which allows it to simultaneously carry out multiple functions, such as searching, tracking, and engaging targets. These advanced features combine to make the radar an impressive engineering achievement and give the Raptor an acute sense of sight (Stimson, 1983 p.577-580).

5.2 PUSHING TECHNOLOGY BOUNDARIES

Engineers at Aerospace Technologies Corporation (ATC) designed the AN/APG-77 radar to extremely demanding performance requirements. Many of the radar's features pushed the technology envelope and required extensive development of new process innovations. For many of the critical components, few suppliers in the world possessed the capabilities and experience necessary to even participate in the development effort. Therefore, ATC often had few choices when selecting key suppliers. For example, only one or two companies had the potential to produce the integrated microwave assemblies required in the backplane array or the array's sophisticated RF components. One engineer described such suppliers' decisions to take on the challenge of meeting the design parameters as "a leap of faith in product and process design". Due to the magnitude and cost of the technology development effort, maintaining multiple sources for an item was often unfeasible and extensive collaboration with suppliers occurred of necessity.

Ambitious technology objectives drove high development costs. Initially, this was less of a concern than today. It was expected that a revolutionary new radar, with performance that far exceeded that of any previous fighter radars, would be expensive. Nevertheless, ATC was not able to hit all of its design targets within the funding originally allotted for EMD. When radar development began, it was assumed that the development and capital costs would be spread over more than 750 planes. The number of planes scheduled for production today is less than half of these original projections. Reductions in the defense budget and unexpected cost overruns in recent years (due to parts obsolescence and other factors) have put pressure on ATC to substantially reduce the radar's price. The magnitude of the original F-22 contract, coupled with its focus on developing exciting new technology, attracted considerable attention from the supplier community. As the size of the program has dwindled and the technology has aged, however, some suppliers that were once eager to participate have become less interested. A positive aspect of the program, however, was that ATC and its suppliers were brought on board early in the design process. Because there was a high level of interest in the program and it had to "prove out" many of the new technologies that were being integrated, the program received more early supplier input than many previous programs. Suppliers were better able to gauge the direction of technology and develop their capabilities accordingly.

In light of the technical challenges that the radar presented, ATC managers and engineers who were interviewed felt that the overall design has been a success. They felt they made concerted efforts early on to carefully consider the effects of design decisions, and that the end product has achieved many remarkable goals. Nevertheless, they acknowledged being able to look back and see areas where engineers could have designed things better. In particular, they are convinced that in the future they can get design and manufacturing engineers to work more closely with each other to reduce the cost and improve the reliability in production. One problem that continues to present a challenge in the F-22 radar program and drives high costs is poor yields in component production processes. Because specifications are so exacting and tolerances are often so tight, high rates of rework are fairly common. It is reported that often expensive parts must be discarded due to poor quality or damage incurred in handling. In many of the labor-intensive processes, interviewees cited variability as a major problem. As a result, engineers have sought to automate these processes when feasible. Even so, production lines sometimes remain dormant for several days to repair capricious machines, which are performing at the absolute limits of their capabilities. Production also frequently stops when components received by suppliers fail to perform at expected levels and must be returned. While part of the yield problem is endemic of pushing the edge of technology, it could be mitigated in some cases by wiser design choices. This requires better communication between design and manufacturing engineers, as well as with suppliers, so that designers become aware of potential difficulties associated with manufacturing their designs.

5.3 SUPPLIER CHARACTERISTICS

5.3.1 Categories of Suppliers

Clearly, not all of ATC's suppliers are equal, nor do all purchasing decisions involve sole-source arrangements. Although for more complicated items the company is often limited in its supplier choices, the purchasing department has more options for common and technologically less advanced components. In fact, in the early 1990s, material managers realized that the company was dealing with too many suppliers and lacked a clear supply chain strategy. With a list of over 1000 approved suppliers, it often had what one manager termed a "fire and forget" policy. Suppliers were replaced frequently and often the company spread its contracts across a large number of suppliers simply to provide business support for all of them. For example, the company had about 68 machining suppliers to which they tried to distribute work evenly. Recognizing the inefficiencies of this system, the company decided to take steps to focus its sourcing efforts. As a result, material managers consulted with a wide range of internal buyers, engineers, and department supervisors and asked them what critical commodities and components were necessary for the company to be successful in the future. Through this process over the past few years it developed a list of key suppliers. This required making some difficult calls and weeding out many long-time suppliers that were not the best in their class. The material department arrived at a list of approximately 100 core suppliers that it designated as “preferred suppliers.” The members of this list were further divided into three categories according to the strategic importance of their technology to ATC. Vendors of common items such as switches and wiring cables, which ATC would never make in-house, were categorized as “parts and components” suppliers. Suppliers of more product-specific but less technologically advanced items, such as machined elements, sheet metal work, castings, and enclosures fell into the “fabricated elements” category. For these items, ATC frequently possesses some in-house technology and performs a careful make-buy analysis before deciding to outsource. Finally, suppliers of technology core to the business, such as gallium arsenide MMICs and RF devices, were labeled “product-line discriminators.” When ATC lacks the in-house capabilities to produce parts in this category, it frequently uses intellectual property agreements to co-develop the technology with these suppliers.

Downsizing and organizing its supply chain has helped the company to focus its efforts towards suppliers and become more thoughtful in sourcing decisions. This has also demonstrated a commitment to the preferred suppliers. Although many non-preferred suppliers remain on older programs due to special product characteristics and the need to minimize re-qualification costs, the goal of the preferred supplier list is to dramatically narrow the choice of suppliers on new programs, with about 80% of total material cost being purchased from preferred suppliers. While there is frequently only one supplier for each of the product-line discriminator items, ATC generally maintains two to four suppliers of various types of parts and components and fabricated elements. The restructuring of the supply chain described above occurred after design of the F-22 radar had begun. It turns out, however, that a high percentage of F-22 suppliers are preferred suppliers. This was attributed to the use of IPTs and emphasis placed on wise selection of suppliers early in the design process.

5.3.2 Challenges Associated with Low Volume

Most of ATC's suppliers are not heavily dependent on it for their business. In fact, for the majority of preferred suppliers, ATC represents less than 10% (and often much less than that) of their revenues. Therefore, ATC's leverage over suppliers from the standpoint of their relative dependence on ATC is relatively low. Since the company buys most parts in very small volumes compared with the suppliers' commercial customers, it often receives low priority attention from the suppliers. For many small electronic components such as processors and RF chips, cell phone makers and computer manufacturers buy lot sizes of 100,000 units while ATC requests lot sizes of 100 to 1,000 units. In an effort to improve its buying power, the material department has attempted to use economic order quantity (EOQ) purchasing when possible. It identifies common components used across several programs and estimates quantities that will be needed over the next few years. It then makes a bulk order for the components and buys ahead of actual need at a reduced price. In addition to reducing price, this enables the company to reduce unexpected fluctuations in components costs. Buying in EOQs, however, generally requires advance funding from the government and a reasonable prediction of upcoming demand, both of which are often difficult to obtain.

Despite the low volumes, many suppliers of advanced electronic components are still interested in ATC's business in order to participate in new technology development. Those interviewed claimed that the defense industry continues to drive many areas of new technology, despite the common perception that the commercial world has outpaced it. Examples include RF components and assemblies and precision manufacturing of microcircuits. Suppliers benefit from the R&D expenditures in connection with the program and from working closely with ATC's engineers to develop the new technology, which they can in turn use in their commercial products. Soon after development, however, commercial demand may begin to far outstrip defense demand. Eventually, orders for the product may outpace the supplier's capacity, as a result of which the supplier may require long lead times to supply its low-volume customers. One example of this phenomenon is the ***tantalum capacitor***. When managers did a study of the longest lead time items required for the F-22 radar, the tantalum capacitor ranked near the top with a lead time of 18 months from time of order. ATC previously worked with the supplier to develop the technology for this capacitor, which has now become very popular for use in small, commercial devices such as pagers and cell phones and is often in worldwide shortage. In another case, ATC maintains a close relationship with a company that produces ASICS. While it accounts for less than 10% of this company's business, ATC helped this company to get started by placing the company's first order, and continues to maintain a close relationship with it. In fact, it is not uncommon for managers at ATC to call up the supplier's CEO to discuss potential designs for next-generation devices.

5.3.3 The Sole Source Dilemma

Although it seeks to avoid them, ATC sometimes finds itself in sole-source relationships with suppliers. These relationships are frequently problematic and costly. As mentioned previously, these situations generally occur because there are no other suppliers with the necessary capabilities, or because developing, qualifying, and maintaining more than one source for complex, low volume components or subsystems would be even more exorbitantly costly and would only increase variability. As a result, ATC becomes highly dependent on these suppliers, which effectively become locked into the radar program. When they perform poorly, ATC's only option is to spend more money to help them. This often involves sending engineering teams to these suppliers to help them improve their processes, which consumes considerable amounts of resources and time. Finding, developing, and training an alternate supplier to produce the highly specialized components, often involving unique processes, would be far too costly. Although considerable collaboration occurs between ATC and such suppliers, the relationships are not often characterized by trust-based partnerships. One IPT lead expressed his frustration with difficulties encountered in these relationships by saying "I hate sole-source contracts." If ATC requires design modifications later in a contract, sole-source suppliers tend to charge extremely high rates to make the changes. Interviewees attributed this behavior to supplier sentiment that they had not received sufficient profit on the original contract terms and viewed changes as an opportunity to recoup some of it. They claimed that this behavior stems from strict government regulation of profit coupled with the high-risk nature of programs, which often results in contractor losses.

5.4 COMMUNICATION WITH SUPPLIERS

Through the interviews with key personnel on the F-22 radar program, several formal and informal mechanisms of communication between ATC and its suppliers were identified. However, it was difficult to assess the extent to which communication has played a role in fostering innovation. As mentioned above, extensive interaction occurs between ATC and suppliers of critical technologies, particularly during development. On the F-22 program, suppliers were involved early in discussing designs tradeoffs and negotiating specifications and requirements. For example, major architectural modifications were made on the radar antenna at the suggestion of a key machining supplier in order to make it easier to machine. One individual felt that while communication with suppliers was good, more would have been greatly beneficial. However, he did not believe it would have considerably affected the design choices that were made. He argued that when pushing technology to the extreme, given very aggressive performance requirements, there is very little design margin. Rather, he suggested that more communication may have improved the "us vs. them" attitude that he perceived to be present in many of the relationships. When asked about the intensity of communication with suppliers, several interviewees stated that even in the absence of routine, formal methods of communication, they are well aware of suppliers' capabilities. This comes through past experience working closely with the same suppliers on previous projects. ATC's engineers reportedly take such knowledge into account when setting design requirements. Yet, as mentioned earlier, ATC still experienced considerable difficulties related to low yields and high variability in components. It seems that despite relatively good communication and understanding of suppliers' capabilities, ATC chose designs that were extremely difficult for suppliers to manufacture, largely because this seemed to be the only way to achieve ambitious performance demands.

The preferred supplier list has been a helpful means of improving interfirm communication over the last few years. The company recently established an internal website on preferred suppliers that contains links to all the suppliers, along with contact names, company profiles, and lists of products (with prices) that the companies have previously supplied. This enables designers to quickly locate potential sources and helps them in design-to-cost efforts. When designing a new product, engineers can quickly estimate prices for various components by comparing them against similar components previously purchased from suppliers. Although these prices are often only rough estimates and do not generally include scrap and rework costs, the website can also be used to obtain a history of past dealings with that supplier, including notes about past problems encountered. If questions about components arise, engineers can quickly locate the appropriate contact at the supplier organization with whom to consult. This saves the time and potential miscommunication that otherwise occasionally results when engineers first call the buyers, who in turn identify and call suppliers and then relay information back to the engineers. The goal is for designers to engage suppliers early, as soon as ATC receives the statement of work (SOW) from its customer and the IPT begins work, to discuss options, identify cost drivers, and determine industry best practices. It should be noted that the preferred supplier list and website were only fairly recently established, whereas most of ATC's F-22 radar suppliers were selected and began work over ten years ago. Therefore, it is difficult to establish a direct link between these practices and innovation on the F-22, although many of the suppliers chosen to participate in the F-22 program later turned out to be preferred suppliers. It was reported, however, that these practices have been successful in improving supplier communication and achieving early supplier involvement in design and development on more recent programs.

ATC also recently began holding yearly conferences with its preferred suppliers. During these events, they share with suppliers directions in which the company is heading and discuss the types of technology being developed for the future. In addition to attending presentations, suppliers are grouped into small teams according to technology area, where they meet with their engineering counterparts from ATC. Suppliers come to know their customer's technology roadmaps in great detail, and must therefore sign proprietary agreements in order to participate. Because suppliers gain a better understanding of the long-term goals of their customer, they are able to perform more accurate resource planning and focus their efforts on the most critical technology areas. Material managers reported that in exchange for such insights, many of the suppliers are willing to engage in up front discussions about new products. They are sometimes even willing to invest their own non-recurring engineering dollars despite the fact that ATC may also be talking with several of their competitors and they may have no guarantee of winning the next contract.

In order to encourage suppliers to share innovative ideas about how to improve existing products, ATC also implemented a formal suggestion system several years ago. Suppliers can submit vendor engineering change requests, known as VECRs, in which they propose design and process improvements and demonstrate the business case for these changes. Suppliers have reportedly used this system in coming forward with a number of innovative ideas, although no specifics about these ideas were given. As a result of concern over the F-22's affordability, the company also created a program Corrective Action Board (CAB) that meets monthly to review cost information and oversee continuous improvement efforts. The board sends letters to high cost suppliers asking them to identify steps they are taking to reduce their major cost drivers. In this way, suppliers have been forced to continually demonstrate that they are making an effort to reduce costs and improve quality. Another measure that reportedly increased supplier enthusiasm for cooperation was an invitation to take part in an F-22 cockpit demonstration. Supplier representatives were able to sit in a cockpit model and experience first-hand the power of the radar and the integrated avionics system. This made them feel more connected with the final product and gave them a greater appreciation for the importance of the technology they supply. These events have helped to create a valuable atmosphere of trust and teamwork between ATC and its supplier community.

5.5 TRAINING OF SUPPLIERS

ATC has conducted training efforts with some of its preferred suppliers. For example, the company recently hosted a conference on using “key characteristics “ in the design process to help engineers identify the essential characteristics desired in new products and focus on the means of achieving them. However, suppliers are reportedly wary of lean training initiatives in which the customer visits their factory. They have the perception that as soon as the customer helps them to identify ways to improve its factory, there will be an immediate demand for cost reductions in exchange. It was also noted by interviewees that some of their supplier companies felt they were already “leaner” than ATC, and therefore, such training would be superfluous.

ATC itself has undertaken a number of lean initiatives and has created a team devoted to instilling lean values across the company. However, changing employees’ mindsets and attitudes is a slow and difficult task, even though opportunities for improvement are ever present. Encouraging employees to find innovative solutions to problems requires more than giving them a set of rules to follow to become lean. Instead, they must be taught to think more broadly and consider the impact of decisions on the efficiency of the system as a whole. A prime example pertains to the traditional lean principle of maintaining low inventory, which ATC employees have rightly strived to follow. In some cases, however, it may make sense to order items in larger quantities than what is immediately needed in order to increase leverage with the supplier or avoid long lead times, particularly for less expensive components. It is reported that this does not always occur because employees sometimes overemphasize inventory minimization and fail to consider the company’s and its suppliers’ larger objectives.

5.6 SHARED SUPPLIER INVESTMENTS

ATC does not generally share in its suppliers' investment expenses. While it may devote substantial resources to help develop suppliers' engineering expertise, it will not typically share in the cost of new machines other capital equipment to enhance production capabilities. Funds for this type of investment are scarce and the payback in terms of reductions in supplier's costs are often reportedly too uncertain. In fact, the nature of the defense funding process makes ATC hesitant to even make long-term investments itself. When the customer renegotiates contracts on a yearly basis, any savings resulting from an investment are translated into a lower price for the product. Therefore, suppliers have difficulty recouping investments with payback periods of several years. Instead, they are in effect penalized by receiving lower revenues and lower profits. Additionally, companies forego investments in themselves or in their suppliers because feel the future of the F-22 is uncertain and the level of funding for future years depends on the vicissitudes of the US Congress. Joint R&D investments with key suppliers do occur, particularly during development phases of new programs, and often lead to technological innovation. Of course, ATC and its suppliers also conduct their own internal R&D to develop new technology and manufacturing capabilities. However, these R&D efforts are usually of a more generic nature and not specific to the F-22 program. Companies would generally only take the step of applying new innovations to the F-22 program if the government granted them funding specifically for this purpose.

To encourage greater investment by the F-22 suppliers in order to reduce cost and increase the program's affordability, the Air Force has initiated a program known as the "War on Cost". Under this program, the government decided to delay the purchase of some planes and instead use the money to fund improvement projects, which will hopefully generate enough savings over the life of the program that all the planned planes can be purchased later under the Congressionally-mandated budget cap for the total cost of production. The War on Cost initiative has three pillars: challenging all program requirements, applying lean principles to reduce overhead costs, and investing in projects focused on cost reduction (Briggs, 2001). Under the Producibility

Improvement Programs (PIP) funding component of the War on Cost initiative, suppliers submit improvement ideas, which are then reviewed by a board of engineers and managers representing the stakeholders (e.g., the F-22 System Program Office, Lockheed Martin Aeronautics, Pratt & Whitney) to assess the feasibility and potential return on investment. The most promising process improvement projects receive funding. These include product redesigns for better producibility, and investment in new production processes. There are some restrictions, however, that limit the ways in which that PIP money can be spent. For example, suppliers may not receive PIP funding to purchase new capital equipment. Under most companies' cost accounting standards (CAS), which must be approved by the government, receiving federal funds for capital expenditures is not permitted.

Interviewees described several examples of successful PIPs which ATC has undertaken. When asked about major innovations which have occurred on the radar, they cited two notable PIP projects. One project involved automating the assembly of the circulator, a major radar component, of which there are 1500 in a complete system. Initially the circulator was built manually and required 52 minutes to complete. Through automation, the production time was reduced to 6-8 minutes and labor and variability have also decreased considerably. Recognizing the importance of this project for increasing F-22 affordability and avoiding program cancellation, ATC contributed several million dollars to the project along with the PIP funding it received.

Another major innovation involved replacing thousands of costly and labor-intensive flex circuit interconnects on the radar's subarray components with automated ribbon bonds. This dramatically reduced hands-on labor, rework, and production time. This project was completed under a contract with ManTech, a part of the Air Force Research Laboratory's Materials and Manufacturing Directorate, and costs were shared between the Air Force and ATC. It required experimentation by ATC engineers to improve the bonding process currently used in assembly of the radar circulators in order to apply it to the entire radar subarray. The project's challenge was achieving ribbon bonds (generally formed at 160 degrees Celsius) at temperatures below 100 degrees Celsius, the maximum temperature that the adhesive used in mounting many of the subarray components can withstand (ManTech website). This challenge was met through research by the company's material scientists. ATC also had to work closely with one of its major suppliers to redesign one of the key subarray components and change its plating. Although both of the innovations reported here were identified by ATC, they would not have been implemented without external funding.

5.7 INTELLECTUAL PROPERTY CONCERNS

Concern about undesirable diffusion of technology sometimes presents a barrier to high degrees of communication and collaboration that may be conducive to innovation. Interviewees reported that diffusion of technology can occur more readily when the majority of major aerospace primes and subcontractors rely on the same key suppliers. Companies must be somewhat cautious when sharing ideas and plans with suppliers, and this can sometimes restrict their willingness to align themselves with particular new suppliers. The customer company's lack of openness about its product's design and functionality also quite often limits the ability of its suppliers to make helpful suggestions or consider ways their components might be better integrated into the customer company's product.

In some cases, ATC must interface with another subcontractor supporting the same prime to ensure proper integration of its product into the larger system assembled by the prime contractor. If the product competes with similar products produced by the subcontractor, the subcontractor will often make very little effort to share helpful information. The prime contractor generally has the ability to share as much information as it deems necessary to get the job done. ATC can contact it when it cannot get sufficient information from the other subcontractor. However, if the prime contractor is disorganized or has a poor understanding of the product ATC provides, the necessary information frequently does not get supplied or is supplied too late.

Interviewees did not feel that assignment of intellectual property rights stemming from joint development work with suppliers was a major concern that discouraged cooperation. They noted that one of the companies involved in these endeavors is usually the clear technology leader, generally making the assignment of patent rights fairly straightforward. Therefore, while fears of disclosing proprietary knowledge to competitors sometimes discourages communication across the supply chain, potential for dissension over legal rights to new knowledge apparently does not significantly discourage participation in collaborative R&D efforts.

5.8 KEY OBSERVATIONS

Several important observations and lessons regarding innovation and supplier relationships can be drawn from this case study. One point that repeatedly arose over the course of interviews was the need for greater communication between those engaged in design and manufacturing. Choices made by designers greatly impact the set of supply chain options available to the company for the remainder of the product's life, which can be a long time in the aerospace context. The potential for future innovation can be enhanced by choosing designs which employ as many standard components as possible and that are available from several suppliers. This provides some flexibility in the choice of specific suppliers and can take advantage of further advances in component technology when suppliers have the incentive to make further improvements in the way they design and build their specific components. The more standard these components are, the greater become the chances that normal market competition provide the needed motivation for continued innovation in the components that are obtained. A supply chain strategy must have the full participation of design engineers for it to truly succeed and increase value across the extended enterprise.

Obtaining the cooperation of design engineers can be challenging, however, as they may be inclined to see their jobs solely in terms of achieving technological objectives and maximizing product performance. They may be generally more fascinated with technology than with manufacturability, and may have chosen their careers in the expectation that they would be able to express their creativity through exciting new designs. They can become very attached to their own ideas and may tend to resist changes perceived to be handicapping their work. Meanwhile, manufacturing and purchasing personnel may fail to understand the technology well enough to make their case to designers. They may not appreciate the designers' challenges and objectives and may frustrate them by making technologically untenable suggestions. Nevertheless, these types of potential barriers must be overcome and collaboration between these groups improved. Designers should especially be encouraged to use standard components whenever possible and to avoid designs which require highly specialized processes. This often means the difference between being saddled by sole-source relationships -- which limit flexibility, require extensive supplier development, and lead to high costs -- and avoiding them. Since designers are often the ones who effectively choose suppliers by involving them early in the design process, they should be encouraged to think strategically about these decisions. In addition to promised technological capabilities, the suppliers' previous performance, reputation, dependence on the customer for business, and potential for holdup due to limited competition are factors that should be taken into account. Manufacturing engineers and purchasing personnel, who generally have more knowledge of all but the first factor, can help to communicate these considerations to designers.

It was observed in this study that minimizing the distance between collaborating individuals and companies greatly enhances communication, and in turn, fosters more innovative ideas. By using a local machining supplier for critical radar array components, ATC's engineers are able to routinely visit and consult with the machinists to troubleshoot problems and optimize the design. This enables rapid experimentation with new ideas and greatly increases understanding between the customer and supplier of each other's capabilities and goals. Interviewees also reported that engineers at ATC on the same project benefited greatly by physically working locationally very close to one another. This encouraged frequent discussion of the design and improved coordination of activities in ways that would not have occurred across greater distances in the company, despite the presence of phone, e-mail, pagers, and similar devices to aid communication. This points to the value that might also be derived from collocating suppliers' engineers at the customer's facility. On the F-22 radar program, collocation rarely occurred, so one can only speculate on its potential impact. However, it is worth considering as a method to further improve interfirm communication and thereby spur greater innovation.

Another important observation concerns the need to understand the impact of design specifications on actual product performance and cost. In many cases, innovation on the radar simply meant working with suppliers to identify unnecessary requirements or those with poor cost-to-performance tradeoffs and eliminating them. Many of the F-22's performance requirements were so demanding that innovation was not an option but a necessity in order to achieve them. While this certainly spurred many technological advancements, it also led to an extremely expensive avionics system. Innovation at any cost is not a desirable goal, and as affordability concerns have grown, so has the need to communicate with suppliers more closely to determine what design targets make sense. At the same time, flexibility from the government customer in defining requirements is also important. It was reported that in order to win contracts for major programs suppliers would attempt to meet nearly any proposed requirement. The case study highlights the importance of early supplier integration into the determination of requirements, as indicated by the subsequent relaxation of some of these requirements to achieve greater affordability.

5.9 CHAPTER SUMMARY

It is clear that a great deal of technological innovation occurred in the design and development of the F-22 radar. However, interviews with individuals at ATC provided few specific examples that could be closely studied. Therefore, it was difficult to pinpoint precise causes of the innovations that occurred, although the underlying driver for many of them seems to have been extremely ambitious performance demands imposed by the customer. A definitive linkage between communication and supplier innovation could not be made, although closer communications with suppliers is clearly identified as an important enabler of mutual process and performance improvements. ATC has taken a number of important steps in recent years to increase communications with its supplier network as a means of strengthening its supplier relationships and encouraging a greater exchange of ideas. ATC has conducted some supplier training activities, but, while these may have helped some suppliers to reduce their costs, the degree to which this contributed to innovation (in the broader sense this word is used in this thesis) was unclear, particularly since some of its suppliers were reportedly already quite “lean” (or at least claimed to have been “more lean” their customer. ATC does engage in joint R&D investments with suppliers in the early phases of new programs such as the F-22. Apart from occasional joint R&D projects, however, sharing in supplier investments has only occurred in the context of PIP funds provided by the Air Force. These funds have helped to support several significant innovations on the radar. It was suggested that greater innovation could have perhaps been spurred through better communication between design and manufacturing engineers and avoidance of sole-source contracting relationships. It was noted that while ambitious performance requirements can act as powerful drivers of innovation, they may also select for costly designs and poor producibility. Finally, the role of PIP funding -- through the War on Cost initiative -- in fostering innovation is indicative of the considerable opportunity that still remains for supplier-based innovations in the defense aerospace industry.

6 CASE STUDY B – F-22 EW SUITE

6.1 BACKGROUND AND INTRODUCTION

6.1.1 Company Profile

Acting as a major subcontractor on the F-22 program, BAE SYSTEMS supplies the electronic warfare (EW) suite, as well as the antenna portion of the plane's CNI and stores management system (SMS). The company ranks as one of Europe's largest defense contractors and also has a significant presence in the US domestic aerospace market. It is the fourth largest defense and aerospace firm in the world. In serving both the civil aircraft market and major defense sectors, BAE SYSTEMS produces avionics, aircraft, communications, radar, ships, space systems, and electronics. Its defense electronics business includes its acquisition of Lockheed Martin's Sanders unit in 2000. This unit, now BAE SYSTEMS Information and Electronic Warfare Systems (IEWS) and headquartered in Nashua, New Hampshire, was the site where this case study was conducted.

6.1.2 Role and Composition of the EW Suite

The function of the plane's electronic warfare suite is to control and exploit the electromagnetic spectrum to support mission goals, while preventing use of the spectrum by enemies. This includes identifying sources of electromagnetic energy for the purpose of immediate threat recognition. Data provided by the EW suite are integrated with data from the radar and CNI (communication, navigation, and identification) system to generate a complete picture of the battle scene and supply the information required to determine appropriate tactical actions.

The EW suite consists of three major boxes, each containing somewhere between ten and sixty digital and RF modules. The **EW array electronics** box ties into the plane's EW antennas. It pre-amplifies and multiplexes aperture signals to outputs to the remote antenna interface unit. The **remote antenna interface unit** (RAIU) performs spatial and frequency selection and handles conversion of signals transmitted between the RF unit and the arrays. Finally, the **RF unit** schedules measurements and commands the arrays and RAIU and processes data from the arrays. Along with these boxes, BAE SYSTEMS also manufactures the EW suite antennas and power supplies. The modules within the boxes are packed with substrates, connectors, and complex circuitry, including numerous microwave monolithic integrated circuits (MMICs), which are critical to the boxes' functions.

MMICs are small, microwave radio frequency (RF) devices responsible for producing the EW's broadband frequency performance. These tiny chips are grown 300 to 400 hundred at a time on 3-inch diameter gallium arsenide (GaAs) wafers. BAE SYSTEMS fabricates forty-three unique MMICs in its facility. While commercial vendors do sell standard off-the-shelf MMICs, these devices usually do not meet the demanding performance requirements and quality standards necessary for integration into the advanced EW suite. One faulty MMIC can cause an entire box to perform poorly and can require extensive troubleshooting to locate the problem. Therefore, engineers prefer to use MMICs that may be rather expensive but are highly reliable and help minimize integration costs, rather than using cheap MMICs that may lead to costly integration failures. Due to their complexity and tight performance margins, MMICs often require extensive tuning to function properly. The tuning process can consume considerable time and expense in manufacturing. In order to prevent environmental degradation, the modules are hermetically sealed once they have been assembled and tested. Fixing problems after this step has been completed is often difficult and costly. Unsealing and then resealing the package can lead to damage that causes the entire module to be discarded.

The EW system's performance requirements flow down from the Air Force to the prime contractor (Lockheed Martin) to systems engineers at BAE SYSTEMS, who divide them among the three major boxes. Within the boxes, requirements are further broken down among the various modules and assigned to module level engineers. Finally, the module requirements are subdivided into requirements for individual MMICs and other components.

6.2 CHARACTERISTICS OF BAE SYSTEMS' SUPPLIERS

The driving technologies in many of the products produced by BAE SYSTEMS, and particularly its EW suite, are RF microwave packaged devices, digital circuit boards, and surface acoustic wave (SAW) devices. BAE SYSTEMS depends heavily on four or five key suppliers for these items, which represent the largest portion of its cost of materials. However, these suppliers all derive less than 30% of their respective total revenues from defense customers like BAE SYSTEMS. The remaining suppliers of BAE SYSTEMS are smaller in terms of their contribution to its material costs for the EW suite. BAE SYSTEMS' top ten suppliers constitute about 65% of total material cost. Many of the suppliers of BAE SYSTEMS are smaller companies with fewer than thirty employees, often delivering niche products. Due to the demanding and unique requirements of its products, BAE SYSTEMS frequently has few suppliers from which it can choose. Several managers noted that reliance on sole-source suppliers often frustrates them, but they find it hard to avoid. Low purchase volumes make it even more difficult to garner many suppliers' attention and encourage competition, particularly in cases where BAE SYSTEMS' contracts would represent only a small share of a company's total revenues. Unfortunately, these characteristics appear to be common features of the defense aerospace subtier supplier base.

6.3 EXAMPLES OF INNOVATION

Due to changing technology and the long EMD phase of the F-22 program, the EW suite has undergone a number of design iterations since EMD began in 1991. The engineering manager at BAE SYSTEMS described it as an iterative process between design and manufacturing, with design changes still occurring as the EMD phase was approaching its conclusion. At the same time, production of PRTV (Production Readiness Test Vehicles) and Lot 1 has already begun and planning for Lots 2 and 3 is underway. As the customer and BAE SYSTEMS negotiate each contract, they must take as their frame of reference the baseline configuration design at its current state. Nevertheless, it is expected that additional modifications will be incorporated throughout the production phase. Many of these modifications are required to fix unforeseen problems, but others represent innovations in product components or manufacturing and testing processes.

A switch to gallium arsenide (GaAs) wafers from traditional silicon wafers has represented a quantum leap in MMIC production technology, leading to significant improvements in performance. However, it is still a relatively immature technology and most semiconductor houses have not yet evolved a common capability in it. Thus, in view of the technological requirements of the subsystem it has had to design and build, BAE SYSTEMS has found it necessary to develop in-house expertise in this area. GaAs is produced in the form of 3-inch diameter cylinders, which are then sliced into thin wafers. BAE SYSTEMS purchases these wafers from suppliers and is able to grow about 300 to 400 tiny MMIC chips on each wafer. See Figure 6.1 below for a representation of the process.

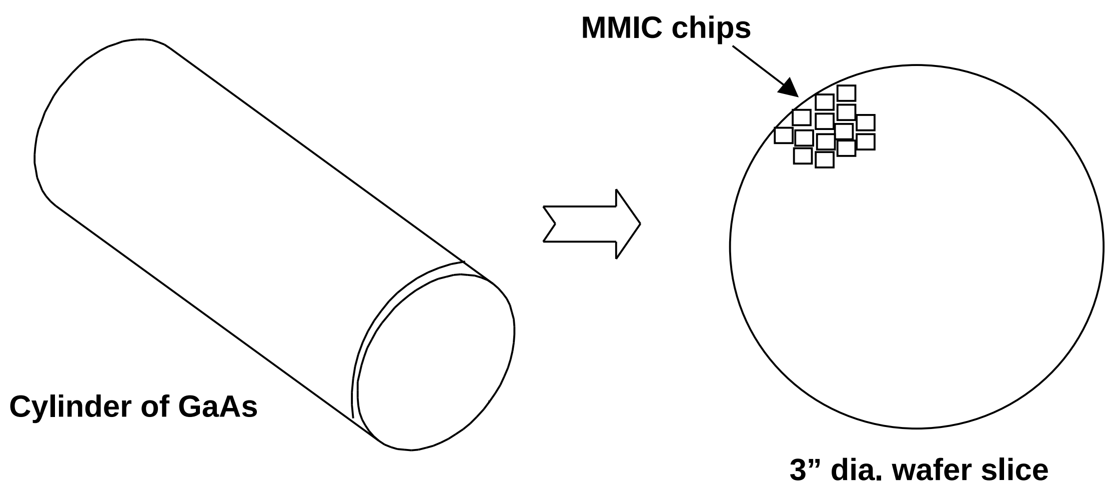

Figure 6.1 – MMIC Production Using GaAs

A further innovation in MMIC production occurred with the advent of a process known as PHEMT, which improved upon the original MESFET process of manufacturing GaAs wafers. The PHEMT process was also originally developed for commercial applications; BAE SYSTEMS adopted it and has redesigned many of its older MESFET devices to replace them with PHEMT devices. However, this transition to PHEMT has not occurred as yet on the F-22 due to the high non-recurring cost involved, although PIPs have been submitted to the customer. BAE SYSTEMS has frequently been able to integrate the functions of several MESFET chips into one PHEMT chip, thereby reducing the number of MMICs in a module. Awareness of new semiconductor technology typically comes through trade shows, publications, and community-specific networks featuring websites, symposia, and other resources. For example, GaAsnet.com is a web-based resource specifically targeting the Gallium Arsenide electronics industry. It provides news, technical features, and company information to help engineers in the telecommunications, consumer electronics, defense, and aerospace industries stay abreast of the latest developments.

BAE SYSTEMS also has a Micro-Electronics Center charged with developing state of the art technologies for military applications and with keeping up with the industry and passing on information about the latest technology to module designers. In this role, the Center acts as a technology clearing-house for the company. The Micro-Electronics Center also conducts a number of internal R&D projects to develop innovative new ideas that will enhance the company's product line. In addition, module designers are reportedly very knowledgeable about their suppliers and can generally stay abreast of new technological developments because there are relatively few capable suppliers.

Another case of innovation is the AlSiC housings used in the EW array. These housings are currently fabricated from a special Aluminum Silicon powder compound to minimize weight. They are small, plated blocks that contain substrate, MMICs and other module circuitry, and connectors. BAE SYSTEMS chose Supplier X because it was the only company capable of producing the 3-dimensional housing designs from AlSiC. Once Supplier X produced the housing, it was then sent to Supplier Y for plating because Supplier X lacked this capability. Supplier Y then returned the part to Supplier X for secondary machining, but received it back a second time to put on the final connectors before shipping it to BAE SYSTEMS. Due to both part travel and the reportedly high price Supplier X has charged for manufacturing, the AlSiC housings have been relatively expensive parts. In fact, BAE SYSTEMS seems to have felt that Supplier X has not been aggressive in its cost reductions due to its market position as sole supplier of AlSiC housings. In an effort to bring down the cost of the numerous housings contained in the EW array while keeping down the weight, BAE SYSTEMS engineers consulted with the company's material specialists and began experimenting with machined titanium. They were able to produce all but one housing design from titanium instead of AlSiC, resulting in a significant weight reduction and considerable cost reduction, assuming these new housings pass upcoming tests. The idea was originally submitted as a PIP proposal, but when BAE SYSTEMS did not receive timely funding for it the company proceeded to invest its own internal funds to carry out the work. Buyers now report that instead of being locked-in to one housing supplier, they can compete the housing production among many machining companies to drive down cost. A second advantage of the titanium housing is that technicians can easily rework it since it contains no O-ring. AlSiC housings, on the other hand, require a special O-ring to hermetically seal them in packages. Rework frequently caused damage to this O-ring and rendered the entire housing useless. Although it did not initially receive financial support from the customer, BAE SYSTEMS pursued this innovation on its own out of a desire to reduce cost in order to ensure the long-term viability of the F-22 program. In the case of this particular innovation, the actual source was BAE SYSTEMS' internal materials engineering expertise. However, an important incentive to pursue it was BAE SYSTEMS own dependence on the program and the desire to drive down costs.

6.4 CUSTOMER-FUNDED INVESTMENT AS AN INNOVATION SOURCE

Lockheed Martin did not initially share in the BAE SYSTEMS' investment costs. However, LM raised the prospect of PIP funding for good investment opportunities, and this has sparked a concerted effort by BAE SYSTEMS to identify innovative new ideas for reducing cost. For example, the company held brainstorming sessions with its engineers, during which they suggested over 700 potential improvements to products and processes. Of these 700 ideas, 55 were chosen for further consideration and written up as formal proposals. The ideas were chosen according to selection criteria that required that the investment have at least a 15 to 1 payback. The 55 chosen ideas represented a cumulative non-recurring engineering (NRE) investment of over $12 million, with a proposed payback of over $270 million over the life of the program. If the investment were to pay for itself in one lot or less, the company implemented it immediately. If several lots were required to recoup the investment, BAE SYSTEMS tried the PIP funding route and $5M of PIP funding was recently awarded to BAE SYSTEMS by Lockheed Martin. BAE SYSTEMS also has an affordability manager, who manages the cost take-out projects and tracks high cost items in search of opportunities for improvement. The company conducted a producibility study in the PRTV phase in which it classified improvement ideas into three categories- “must make”, “should make”, and “nice to make”. Improvements in the “must make” category, considered very critical, were undertaken immediately, regardless of their payback time profiles or the availability of customer funding. “Should make” improvements have been undertaken if they are expected to pay for themselves by the end of PRTV, and “nice to make” improvements have generally been postponed in the absence of external funding.

Tuning modules after assembly consumes a considerable portion of manufacturing time and cost. Therefore, managers have focused on improving the tuning process to decrease lead times and labor costs while increasing its reliability. Because tuning is an imprecise, trial-and-error type procedure, experience of technicians and consistency of the product design plays a significant role in the efficiency of the process. Frequent modifications to the modules through engineering change orders (ECOs) and high turnover of assembly workers have hampered efforts to achieve consistency and streamline operations. The development of guidebooks based on technicians’ experiences and cross-training of employees to enhance their range of skills has helped somewhat. More important, however, has been automating the process when possible by investing in sophisticated, but expensive, diagnostic equipment. This speeds up the process and minimizes variability. BAE SYSTEMS has made many NRE investments in diagnostic equipment and other machines in order to lower the cost curves to which they had originally agreed for the program. However, managers stated that some investments which would save the program money are never made or are postponed because the company cannot afford to make them all in a given year. They suggested that customer sharing in NRE expenses would benefit the program as a whole over the long run by reducing total cost. NRE encompasses investments in equipment specific to a contract, such as test stands and tooling. Capital equipment, on the other hand, is defined as general purpose equipment that may be used on a variety of programs and products. The customer generally has visibility of the return on investment (ROI) of NRE but not of the ROI on capital investments. Lockheed Martin does help BAE SYSTEMS to reduce the burden of its NRE investment expenses by coordinating with the US Government to locate unused equipment made available from its warehouses. Unfortunately, this often represents more of a hindrance than an aid to BAE SYSTEMS. BAE SYSTEMS must give Lockheed Martin a full list of its intended special test equipment (STE) investments and cannot make any purchases until Lockheed Martin confirms that the government does not have the required equipment available at its own facilities. The process entails considerable paperwork and tends to delay investments in STE, often by several months.

One example of an innovation that would significantly reduce cost but require considerable up-front investment (making it a candidate for PIP funding) is a new digital receiver unit for the EW suite. Engineers believe the digital receiver will enable them to eliminate a number of expensive parts in the current receiver design. However, it would require them to redesign a major portion of the RF unit and would cost approximately $50 million to implement. BAE SYSTEMS cannot afford to fund this effort on its own and has requested funds from the government to support it. Unfortunately, it has encountered delays in getting approval and in receiving PIP funding. The design changes will take a considerable amount of time to complete. Hence, the company must begin planning now in order to incorporate the design changes into the aircraft several lots later in the future. Due to the importance of this project, Lockheed Martin has agreed to help support it with funds until government funding becomes available. BAE SYSTEMS has also gone ahead and invested a considerable amount of its own resources to commence work. The company is motivated to self-fund this endeavor by its desire to achieve customer objectives for significant cost reduction as well as by the expectation that it may generate offshoot technology – which would provide benefits on other programs and possibly lead to a spin-off company. If successful, the digital receiver design will significantly reduce the long-term contract value of the EW suite BAE SYSTEMS supplies. Since the customer generally does not grant a larger profit margin on the contract as a reward for reducing cost, BAE SYSTEMS may be effectively shrinking its total profit on the contract. Even if the project were completely funded by the customer, it would be counter to the company's interests to propose such an innovative step forward unless it would generate valuable offshoot technology and/or tangible additional goodwill on the part of BAE SYSTEMS' customers (i.e. both Lockheed Martin and, indirectly, the Air Force) leading to a stronger long-term relationship. In this case, major drivers of innovation include BAE SYSTEMS' dependence on the success of the F-22 program, its desire to cultivate the goodwill of key customers on which it will depend for future business, and the prospect of developing lucrative off-shoot technology.

In terms of its own suppliers, BAE SYSTEMS frequently invests time and provides training as well as engineering resources, but does not usually share in equipment investments. Its engineers often spend time helping suppliers to develop necessary capabilities and ensuring that their products consistently meet the required specifications. Managers noted that many of their suppliers are small companies, which are unwilling or lack the resources to make expensive investments without help from their customer. BAE SYSTEMS would like to fund more investment in suppliers to help them purchase cost-saving equipment, but cannot afford to do so. For example, many suppliers test their products manually on bench test equipment. Improvement teams have recommended replacing bench testing with automated test equipment, but suppliers have never received any funding for such equipment. These ideas were submitted as PIPs to Lockheed Martin but reportedly have not been approved. One manager was very frustrated with the lack of PIP funding to BAE SYSTEMS, despite the submittal of numerous proposals. He noted that the company's suppliers eventually begin to believe that BAE SYSTEMS is not serious about improvement when they never receive the money to implement suggestions. As a result, they lose the motivation to come forth with new ideas. He felt that considerable time has been expended promoting initiatives and holding conferences designed to help F-22 suppliers reduce the cost, with acquisition personnel and the prime contractors constantly stressing the need to improve. As a result, suppliers have worked hard to identify and suggest a myriad of good ideas. However, he perceived that beyond a lot of talk, little has been done to actually carry out improvements by providing the necessary financial support.

6.5 SUPPLIER TRAINING

Lockheed Martin has conducted a number of lean training initiatives with BAE SYSTEMS. Managers at BAE SYSTEMS reported that these initiatives have made a significant impact on the cost of manufacturing by helping to identify ways to reduce the distance traveled by parts on the factory floor, eliminate waste, and streamline production. BAE SYSTEMS has also conducted programs to train its major suppliers. In an initiative known as Value Focused Relations (VFR), the company has conducted an extensive review of its top F-22 suppliers. Through this effort, it has examined the books of its suppliers to identify cost drivers, major problems encountered, and supplier strengths and weaknesses. VFR has included a day of supplier training followed by day of intensive brainstorming to identify new ideas for improvement. Key personnel from the both the supplier and BAE SYSTEMS have then formed four teams (manufacturing, engineering, material, and process teams), based on their respective job functions. Each of these teams has discussed the ideas generated from the brainstorming session pertaining to its focus, assessing their feasibility and potential impact. BAE SYSTEMS has discovered through these supplier visits that many suppliers were conducting extra testing that was driving up costs. For example, 40% of one key supplier's total unit cost consisted of testing. As a result, many changes to the test specifications have been identified. Many other promising improvement ideas have also been submitted for PIP funding. Again, however, few of the ideas have actually received the financial backing to implement them. This may be due in part to the fact that some of these ideas would require changes in the system that are blocked by past design decisions that cannot be easily redone. If this is the case, however, it is presumably due to design issues that are visible only to the prime contractor, since BAE SYSTEMS's engineers work with suppliers and jointly discuss the ideas before they are submitted for approval.

During the VFR process, distrust of the intentions of BAE SYSTEMS made some suppliers initially reluctant to accept its training. The suppliers feared that BAE SYSTEMS would use factory visits to closely observe and learn to imitate their proprietary processes, eventually shifting production of the components in-house and cutting them out of the loop. Over time these fears faded and even the most secretive suppliers became much more receptive to a closer and more open relationship with BAE SYSTEMS. BAE SYSTEMS managers who participated in these training visits, however, observed that many sole-source suppliers declined to implement many of their suggestions, at least openly. In actuality, managers believe that these suppliers did listen and benefit from the training and on-site evaluations. However, they have not always admitted taking the customer's advice in order to avoid giving the customer any justification for requesting price reductions. In effect, according to BAE SYSTEMS, the suppliers received helpful training but were reluctant to reduce their price in exchange. One manufacturing manager reported spending over a week at a critical supplier's facility.   Yet the supplier's price remained virtually unchanged afterwards. This was rarely the case where two or more potential suppliers could compete for the customer's business. Rather, these competing suppliers demonstrated an eagerness for help and a willingness to act promptly on any recommendations offered by BAE SYSTEMS. Their behavior is reported to have been influenced by a strong fear of losing business to their competitors.

6.6 FORMS AND ROLES OF COMMUNICATION

BAE SYSTEMS and Lockheed Martin manufacturing personnel engage in weekly teleconferences to discuss issues and problems that arise, as well as to confirm or negotiate changes in delivery schedules. Lockheed Martin occasionally requests that items be delivered earlier than planned. BAE SYSTEMS seeks to accommodate these requests whenever possible by shifting production resources among different projects. In addition, the technical engineering lead for avionics from Lockheed Martin visits BAE SYSTEMS frequently. He understands the company's product well and collaboration between him and the engineers of BAE SYSTEMS has been critical to ensuring that the EW suite integrates properly into the rest of the F-22 avionics system. Nevertheless, interviewees have expressed some concern about engineers and managers representing Lockheed Martin who are principally airframers and who may not fully understand the avionics business well. In particular, it is reported that these managers and engineers may not, in fact, be fully familiar with manufacturing challenges facing BAE SYSTEMS and may have an insufficient understanding of the company's major cost drivers. For example, they may exhibit a lack of understanding of why the testing of the product is such an expensive process. Interviewees felt that both sides would benefit from more site visits by Lockheed Martin personnel.

Although a high degree of communication occurs between Lockheed Martin and BAE SYSTEMS, it is sometimes disjointed and occasionally leads to confusion because it involves so many individuals and groups. Although there are many positive aspects of frequent, informal communication, managers noted that it was sometimes difficult to keep track of all the changes taking place. As a result, there may be uncertainty about which drawings and specifications constitute the current product baseline, or what is the latest delivery priority.

BAE SYSTEMS also reported that its customer sometimes communicates poorly in a contractual sense. Managers did not perceive a strong desire by Lockheed Martin to see its supplier succeed financially as well as technically. According to these managers, promises were occasionally broken and deals were not always executed in a timely manner. It was reported that the customer often failed to compensate BAE SYSTEMS for making requested design changes, because it felt that the changes were not substantial enough to warrant compensation beyond the contract terms. BAE SYSTEMS managers expressed their understanding that the customer does not have unlimited resources and cannot afford to fund every minor modification. However, there seemed to be disagreement between the two companies as to which modifications were indeed minor and which deserved additional compensation. BAE SYSTEMS seemed to feel that the number of uncompensated changes required stretched their financial resources to the limit.

Last minute changes in design or delivery schedule by the customer have also occasionally created complications for BAE SYSTEMS. It was noted that in one instance Lockheed Martin requested significant product changes only three days before the shipping date. In other cases products languish on the factory floor well past the intended shipping date because Lockheed Martin reportedly failed to sign the necessary requirements waivers. Regulations require that these waivers be signed before BAE SYSTEMS can deliver its product. Although the waivers would normally be approved, it was pointed out that Lockheed Martin sometimes refrains from signing them if the product is not needed right away. This demoralizes manufacturing employees who worked hard to ensure that the product was ready to ship on-time, and it acts as a disincentive to future responsiveness.

The focus by BAE SYSTEMS on the Value Focused Relations initiative and frequent visits by engineers to develop supplier capabilities have increased communication with its suppliers. BAE SYSTEMS has also invited a few of its most important suppliers to tour its facility to learn from its processes and consider how they might benefit from investing in similar automated equipment. However, suppliers generally know little about the company's larger goals and challenges beyond the immediate product specifications that they receive. This is largely due to the desire for secrecy, which has two components. One is the company's desire to keep the EW's overall design and performance proprietary. The other is the necessity for military secrecy, where much of the technical information is highly classified and where there is a natural need to let specific suppliers know only what they narrowly need to know in performing their particular tasks. As a result, engineers refrain from sharing more information than they feel might be necessary for the suppliers to make their respective components. Unfortunately, the suppliers are then less aware of their customers' higher level objectives and, as a result, feel less empowered to recommend changes that might improve the overall design, functionality, and performance of the subsystem being designed and built. Secrecy limits the company's ability to take advantage of potential supplier capabilities and innovations and makes it difficult for suppliers to identify user needs that they might fill. In order to mitigate this problem, BAE SYSTEMS recognizes the need to encourage suppliers to more clearly communicate their cost drivers and lay out all their design options. In this way, BAE SYSTEMS' engineers can evaluate tradeoffs and identify opportunities for improvement themselves.

6.7 CONTRACT STRUCTURE

While the cost-plus EMD phase of the F-22 program is still on-going, PRTV and low-rate production Lots 1 through 5 (as well as all future lots) are structured as fixed price contracts, with each lot price being negotiated just before its production begins. This structure is unusual for the early production of a large and complex new military program, where contracts with suppliers are typically on a cost-plus basis until full-scale production begins. The fixed price contract incentivizes BAE SYSTEMS to make improvements or investments that immediately reduce its cost and pay for themselves in a short period of time, such as a year. However, cost savings cannot generally be realized as additional profits beyond one year because the contracts will be renegotiated. Changes in the company's cost structure will be mirrored by changes in the final price they receive from the prime contractor on future lots. According to the company's managers, this contracting structure acts as a major disincentive to innovation among suppliers. Innovative ideas are effectively not rewarded beyond a year. The digital receiver design mentioned above serves as a prime example. This innovation will actually reduce the company's profits over the life of the program.

The fact that changes as part of EMD are occurring concurrently with early production also makes fixed-price contracting troublesome. The supplier must estimate its costs and agree upon a production price at the same time that its baseline design is undergoing continual modification. For example, when BAE SYSTEMS negotiated Lot 1 prices and sent out its proposal for Lot 2, it only had 30% of the actuals from PRTV. Even if more actuals had been available, they may not have helped because the PRTV design differs so much from the Lot 1 design. BAE SYSTEMS managers suggested that a cost-plus contract structure with a cost incentive would have probably been more efficient in PRTV and in low-rate initial production. This would have eliminated the difficult and time-consuming task of estimating future costs based on incomplete information and repeatedly negotiating future contract prices. In addition, a cost-plus structure would have permitted the government much closer observance of the company's cost structures before full-scale production begins. If the customer insists on using a fixed-price contract, however, managers felt that multi-year contracts would help to motivate innovative behavior. It was also suggested that rather than the government fixing the number of planes it will purchase and setting a target for the total cost, it should fix the total pool of money and ask companies to build as many planes as possible subject to that constraint. By reducing their costs, suppliers would then not be simply reducing their profit per plane on a predetermined number of planes, but would be creating the opportunity to make profits on a larger number of planes. Otherwise, suppliers that improve are essentially giving a portion of their profits to other suppliers that may be lagging in their performance.

6.8 KEY OBSERVATIONS

This case study suggests that there are several barriers to greater innovation across the supply chain. These include low product volumes and sole-source subcontracting that may provide insufficient economic incentives for innovative behavior on the part of lower-tier suppliers. Also, contract structures being employed often fail to reward innovative behavior. Many of the company's sole source suppliers do not depend heavily on BAE SYSTEMS for their revenues nor do they fear a loss in their market shares. As a result, BAE SYSTEMS has a difficult time incentivizing them to innovate to share in the gains. Consequently, these relationships often result in very high prices for the items procured. In order to mitigate or avoid these problems, companies should begin with a very careful make-buy analysis in cases where it is clear that outsourcing would mean dependence on a single source for capacity as well as for knowledge (Fine 1998). The beneficiary supplier may possess valuable capabilities and experience derived from previous defense work or commercial industry that would be hard to duplicate. On the other hand, the item to be procured may be so unique that it may not necessarily cost a lot more to produce it internally by developing in-house production capabilities compared with the cost if it were outsourced. Perhaps the extra cost of in-house production would be offset by the lifetime savings from not being dependent on a single supplier and by the additional learning acquired from doing it internally. In cases where sole-sourcing is the only option, perhaps a different contract structure would be more effective. Instead of a fixed price agreement in which the supplier essentially acts as a price-taker, perhaps a cost-plus arrangement would be better. Under such a cost-plus “regime”, the customer company could guarantee the supplier a certain profit margin in exchange for the right to closely observe the supplier’s cost structure. The customer could then identify inefficiencies, recommend improvements in the supplier’s processes, and verify that these suggestions were implemented.

Suppliers would probably also be more innovative if they were able to operate in higher production volumes. Uncertainty about the future of the F-22 program prevents companies from procuring material beyond the upcoming production lot. If low-volume yearly purchases could be consolidated into multi-year purchases, more suppliers would be attracted to compete for each order, customers could reap volume discounts, and many suppliers would be more willing to invest in equipment with longer-term payoff. Along these lines, one manager at BAE SYSTEMS even recommended consolidating orders by the major avionics subcontractors (like BAE SYSTEMS, Raytheon, TRW, and Northrop Grumman) for common critical components. For example, nearly all of these companies procure similar MMIC chips and integrated circuits from companies like

Remec Microwave and Tyco Electronics. Although the components may not be identical, they basically all require the same equipment to manufacture and test them. Instead of a company like Remec Microwave having separate manufacturing lines for each customer, these lines could be combined to form a common F-22 production area. This would ensure a steady volume of work through the area rather than separate, specialized lines for each company, which are active for only a portion of the year and are then dismantled and set up again the following year. Processes would become more efficient through standardization and employees would continually learn and gain experience. This would foster innovative improvements in design and manufacturing and reduce overall cost. The company's managers do not feel that concerns about protection of intellectual property would prevent such consolidation. In selected cases where projects with suppliers entail highly proprietary technical know-how, a separate portion of the supplier's plant could be used. Otherwise, being able to observe a supplier producing items for other subcontractors is reportedly neither a concern nor an uncommon phenomenon in today's environment.

Lack of up-front investment to support suppliers' innovative ideas and thus enable future cost reduction seems to be a problem. Both uncertainty about the program's future and the limited size of many suppliers' capital pools contribute to this under-investment. If the government cannot grant suppliers long-term contracts nor guarantee that the program will remain active and will be of reasonable size, suppliers will be less inclined to risk investments with longer payback periods. The government customer can step in and help by funding promising opportunities in order to maximize long-term affordability. As with the War on Cost Initiative, this may mean devoting even more of its program funding in early years to product and process improvements and delaying a greater portion of the initial production quantities. Naturally, doing so depends partially on the cooperation of the US Congress in the funding process. Of course, acquisition personnel must also find and strike the right balance between fewer planes sooner (i.e., funding less investment) or more planes later (i.e., greater initial investment to reduce cost later). This tradeoff will depend on the military's current defense needs and the rate of return on investment. Based on interviews, however, it appears that many supplier investment opportunities with significant payback potential (as much as 15 to 1 or even greater savings) are being left unfunded. Although PIP funding through the War on Cost has been a step in the right direction, most suggestions with paybacks of less than 15 to 1 are not likely to be contenders for the available funds. This case study provides evidence for the argument that a great deal of effort has been devoted to identifying improvement opportunities among suppliers but little has been done to actually capitalize on them. It seems the government would be wise to provide considerably more funding to support smart investments by suppliers.

As this case study demonstrates, good communication and supplier training have positive impacts on supplier innovation. BAE SYSTEMS reported that close interaction with the Lockheed Martin personnel knowledgeable about the EW system and about the capabilities of BAE SYSTEMS was very helpful. This interaction included frequent site visits and teleconferencing to coordinate production schedules, troubleshoot unreliable or overly expensive production processes, negotiate requirements, and ensure proper system integration. Lean training also helped BAE SYSTEMS to identify efficiency gains in its manufacturing system. The company's Value Focused Relations initiative with its top suppliers resulted in many new ideas for improving suppliers' products and for reducing costs.

One barrier to greater communication, however, has been secrecy surrounding the design and overall performance objectives of the system into which the supplier's component must be integrated. In addition, the company's EW suite relies on highly sophisticated and unique electronics technology that few suppliers and even few individuals at the customer organization understand well. Preserving preeminence in this technology, rather than simply being good at integrating the innovative ideas of its suppliers into a well-functioning system, is essential to the company's success. Therefore, this sometimes provides a disincentive for greater sharing of information with external organizations.

Maintaining an awareness of industry trends and developments has been important in capitalizing on key innovations in microwave electronics, a core technology of many of the company's products. This has involved proactive nurturing of both module designers familiar with supplier capabilities and of technological gatekeepers who scan the entire industry by participating in conferences, trade shows, research symposia, and other initiatives to keep track of new technology.

Although customer companies have taken strides to foster innovation among their suppliers through investment, communication, and training, the contract structures they have used have done a poor job of rewarding supplier-generated innovations. BAE SYSTEMS managers reported that little financial incentives exist to encourage its major suppliers and, in turn, the suppliers of these major suppliers, to innovate. Reductions in cost only get translated into reductions in the price received from the customer, resulting in lower total profit. Despite being negotiated as fixed-price, the contracts have effectively become like cost-plus contracts, only with a penalty to the supplier if its costs unexpectedly rise above a pre-negotiated target in a given year. Concurrency in design and production has made it extremely difficult for suppliers to estimate future costs. A large number of engineering change orders (ECOs) during production has made it especially difficult to standardize processes, keep track of changes, and coordinate with suppliers and with the customer.

Managers reported that the primary incentive to innovate and reduce costs, to-date, is to ensure the long-term viability of the program. Companies realize that the entire supply chain must achieve affordability goals in order to maintain the favor of the US Congress and to ensure that the F-22 program is not altogether cancelled. This incentive is fairly strong for larger defense companies, such as BAE SYSTEMS, with relatively sizeable F-22 contracts. However, it does very little to motivate many of the subtier suppliers because they do not depend heavily on the F-22 program for their revenues. Yet, these subtier suppliers combined represent roughly one-third of the total program cost[6]. Larger defense companies such as BAE SYSTEMS are willing to absorb some risks and costs to support program objectives. On the other hand, they do not want to make too many sacrifices, since by reducing their own costs they effectively reduce the pressure on other suppliers to cut their own costs to preserve the program.

6.9 CHAPTER SUMMARY

MMICs play a critical role in many avionics systems such as the EW suite, and advances in this technology area has been (and will likely continue to be) an important form of innovation contributing to performance enhancements. These innovations arise and are diffused through a variety of interrelated channels, including research by commercial industry, networks of technology developers, and internal research centers at major defense companies such as BAE SYSTEMS. Communication between BAE SYSTEMS and its customer has been important in coordinating activities and ensuring proper integration of systems. BAE SYSTEMS and its suppliers, through working closely together, have been able to identify many opportunities for product and process improvements. However, many of these ideas require considerable upfront funding to be implemented, which many suppliers have been hesitant to make alone in the face of capital resource constraints, program uncertainty, and insufficient contractual incentives. PIP funding by the government has helped to a limited degree in this regard by providing some financial support, although it appears more could be done. In some cases (such as BAE SYSTEMS) the desire to reduce costs in order to preserve the program has provided a major incentive to pursue innovation. The yearly, fixed-price nature of contracts has proven problematic due to the difficulty of estimating prices in early production (while significant changes continue to be made to the design) and the lack of reward they provide for innovations with longer-term payoffs.

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[6] Rich Briggs. "F-22 Affordability, Supplier Involvement and The War on Cost", Presentation at Lean Aerospace Initiative (LAI) Plenary Conference, April 11, 2001.

7 SUBTIER SUPPLIERS TO AEROSPACE TECHNOLOGIES CORPORATION

7.1 SUPPLIER A

Supplier A Printed Circuit Group consists of 11 separate facilities under the Electronics Division of Supplier A International, a large multi-national conglomerate of companies spanning several industries. Within the Printed Circuit Group, there are four facilities specializing in defense products, two of which were purchased from other companies in recent acquisitions. Defense business accounts for less than 10% of the Printed Circuit Group's total revenues and a miniscule fraction of Supplier A International's total corporate revenues. Nevertheless, the defense industry remains very important to employees at the four defense-specific facilities, whose jobs depend on this source of revenue. On the F-22 program, Supplier A supplies printed circuit boards (PCB) to both BAE SYSTEMS and Aerospace Technologies Corporation (ATC) for the EW suite and radar, respectively. The PCBs consist of long strips of multi-layer fiberglass boards coated with circuitry and mounted with electronic components. The core technology has existed for over a decade and many suppliers manufacture PCBs. However, Supplier A specializes in manufacturing complex, multi-layer PCB configurations on large boards, often with very tight tolerances. Supplier A is one of only two or three companies in the world capable of producing the sophisticated designs required by many defense applications.

The boards that Supplier A supplies to BAE SYSTEMS and ATC were designed by these customer companies, while Supplier A developed the necessary manufacturing capability. Unfortunately, early versions of the boards were poorly designed for manufacturability. The two customer companies have taken steps to remedy this problem on more recent generations. ATC, in particular, is now working very closely with Supplier A to design a fourth generation PCB to be used in both the F-22 radar and several other applications. It has established an IPT team structure that includes both its own designers and Supplier A's engineers. ATC's engineers visit Supplier A approximately every two weeks to discuss their designs. Because ATC has been very receptive to suggestions for design improvements, this type of feedback has become a frequent occurrence in the relationship. One innovative outcome of this collaboration has been a consolidation of 99 individual boards into one large board. This is expected to yield major benefits in terms of both reliability and cost.

ATC has begun to look across its programs for ways to build commonality into its board designs. By discussing ideas with Supplier A, it has been able to identify such opportunities and create designs with multiple applications. ATC recently held a conference in which it shared confidential information with Supplier A regarding future development efforts. Those interviewed felt that this gave Supplier A important insights into directions it should pursue to continue satisfying the technology needs of its customer.

Another way ATC has sought to improve the design of its PCBs is by co-locating new PCB design engineers for a brief time at Supplier A. This has given them the opportunity to learn first-hand from Supplier A's engineers the elements of good designs and has improved long-term communication. The attitude of the buyer at ATC is reportedly to "stay out of the way" and allow engineers at the two companies to work closely together to develop the right design.

Supplier A has experienced a lesser degree of collaboration with BAE SYSTEMS. This was attributed to the decentralized nature of the business of BAE SYSTEMS, which consists of numerous facilities located around the world that are often perceived to act as separate companies. However, BAE SYSTEMS has employed "synergy teams" that have looked at ways to improve the efficiency of its purchasing procedures. After surveying the capabilities of many suppliers in the PCB industry, it has dramatically reduced the number of suppliers it plans to use and has identified Supplier A as a critical source. Less attention has been given to improving the manufacturability of its PCB designs and the level of commonality across programs. Of course, such efforts may follow once BAE SYSTEMS has had time to fully integrate its recent acquisition of several electronics companies (including the former Sanders unit of Lockheed Martin). Supplier A has sought to increase communication with BAE SYSTEMS and other customers by holding technology roadmap seminars. It has invited engineers from all divisions of customer companies to come and learn about the technological capabilities Supplier A is developing. This is part of an effort to let PCB designers know ahead of time the types of manufacturing complexity they can confidently build into future designs.

When customer companies design boards and select their components, poor design decisions can often leave Supplier A stuck with bad relationships with its own suppliers. For example, if ATC's board specifies an extremely unusual or unique component, Supplier A may only be able to procure it from a single source and the cost would quite likely be rather high. In one particular case, BAE SYSTEMS specified that two boards be joined to special copper-molybdenum core made by only one supplier. Unfortunately, Supplier A had a very difficult time managing this supplier. Eventually, BAE SYSTEMS stepped in to manage that supplier. Supplier A shipped the two boards to BAE SYSTEMS, where they were joined with that supplier's core. All three pieces were then sent back to Supplier A for a final bonding process.

Supplier A's defense business is extremely capital intensive. Performing complicated layering operations and achieving tight tolerances requires expensive equipment. The quality and costs of boards could be improved with greater capital expenditure. However, the uncertainty of the defense environment discourages such investments. The possibility that programs may be cancelled at any time discourages investment in equipment with long payback periods. In addition, changes in board configurations can eliminate the usefulness of purchased equipment. For example, Supplier A recently purchased a $500,000 RF test machine for two boards. The customer recently changed the design slightly and the testing has since become unnecessary. To avoid such situations, Supplier A has begun asking customers like ATC to pay for test equipment. It has also asked ATC to share in the cost of capital equipment to improve its manufacturing efficiency. For example, a board it currently manufacturers for ATC requires technicians to hand-solder 1000 connectors. This manual activity could be replaced by a soft-beam solder machine that would cost over $2 million. In the long run, this would be a cost-effective investment, but Supplier A is hesitant to take that risk without some financial support and assurances from its customer.

ATC and BAE SYSTEMS both exert constant pressure for price reduction. However, Supplier A has considerable leverage as one of the only suppliers possessing critical PCB capabilities. While in the past they have occasionally refused to meet demands to reduce prices on some board configurations, those interviewed did not feel that Supplier A ever demands unreasonable prices. Supplier A remains eager to retain its defense business and even offers volume discounts when major customers exceed certain targets for total sales. In some cases, Supplier A's redesign suggestions have dramatically reduced the cost of boards and correspondingly decreased Supplier A's revenue. However, Supplier A continues making such suggestions in the interest of constantly improving its own capabilities and maintaining a strong relationship with major customers.

7.2 SUPPLIER B

Supplier B is a small manufacturer of thin and thick film circuit components and microelectronic inductors. While the company's focus is high reliability components for the aerospace and defense industries, it has a growing commercial base which now represents close to 60% of its business. Supplier B specializes in designing, prototyping, and manufacturing components to customer needs, typically in low volumes (although a few high production lines also exist). Supplier B supplies proprietary ferrite wafer elements for use in the F-22 electronically-steered array of the radar produced by ATC. This is a critical part of the radar and plays an important role in enabling its superior performance. ATC actually supplies the specialized ferrite material to Supplier B, which then processes it into wafer elements. F-22 business accounts for about $150,000 – $200,000 of Supplier B's annual revenues, which is about 4-5% of its total annual sales.

Innovation in the product Supplier B supplies to ATC has not come through enhancing the product's actual performance, but rather in developing a reliable process for manufacturing it. The technological challenges stem from the brittle nature of the ferrite, which becomes useless if blistered or cracked during the intricate manufacturing operations required to transform it into the final product. While technological progress has been made, yields are still considered unacceptable and variation is high. Supplier B and ATC engineers continue to work on solving the remaining problems in the manufacturing process. Supplier B is one of only four companies in the country that work with ferrite, a material that is notorious for being difficult to process. The F-22 product requires particularly complex operations and Supplier B faces little competition from others.

Supplier B joined ATC on the F-22 program about six years ago. Those interviewed described the company's relationship with ATC as frustrating compared with other active programs in which Supplier B is engaged. They felt that the technical support received from their customer has been inadequate, which has hindered efforts to improve the production process and reduce costs. While ATC has frequently sent its people to visit Supplier B, these people have generally focused their attention on business matters rather than on technical issues. Supplier B engineers have complained about the material supplied by ATC, which reportedly suffers from certain quality problems that make the material particularly difficult to process. This increases the propensity for producing a defective product. It has been reported that small defects, known as chip-outs, frequently occur during a sawing step. Depending on the size and location, chip-outs may significantly affect performance, but there has been inadequate emphasis on this issue by ATC until recently. Supplier B continues to run its production operation at unacceptable yields, which increase the price. It should be noted that all known saw and blade manufacturers have been contacted to discover if there is a way to reduce chip-outs during sawing. To date, no one has come up with a substantial improvement in the process.

In search of a solution to the problem, Supplier B has experimented with laser cutting the ferrite. This leaves a small chamfer along the cut that is unacceptable according to ATC's original specifications. However, the criticality of this cut has not been thoroughly investigated. There is some doubt regarding how much chamfer slope and roughness might be acceptable. Also, there is slag on the edges that is created by the laser cutting process and which needs to be removed. It was noted that ATC keeps most of its process information confidential. Although those interviewed felt that ATC was reluctant to accept suggestions for improving the ferrite material it supplies, they noted that it has nevertheless taken several helpful steps. ATC has agreed to mark the roughly 1 out of 5 parts that clearly have flaws. It has also begun punching the necessary holes in the material itself, while the material is still in a green state. This drastically reduces stress fractures. In addition, ATC has just assigned a new technical liaison to work with Supplier B, which is expected to help to solve the problems.

One event that temporarily strained the relationship between Supplier B and ATC was an incorrect price quote that had to be voided. One of Supplier B's salesmen misquoted a production order by mistakenly basing calculations on an unusually high yield rate of a sample run. This rate did not accurately reflect the large variation in yields experienced between batches of production. When management discovered that they would be suffering severe financial losses at the given price, they refused the order. This naturally upset the customer. While those interviewed understood the customer's frustration, they felt that ATC could place more emphasis on technical support that would enable the achievement of better yields and reduced prices. They believe that the customer's behavior is symptomatic of a defense industry-wide focus on short-term cost at the expense of quality. Despite these strains, Supplier B highly values its relationship with ATC. It expects to work closely with its customer to further develop technological capabilities for producing the critical radar components. Recently, ATC has been actively concerned with resolving the difficult technical problems inherent in this component. ATC has recognized Supplier B achievements and demonstrated its appreciation through an Outstanding Supplier award. This award was greatly appreciated and helped to increase goodwill between the two companies.

7.3 SUPPLIER C

Supplier C is a division of Supplier C International, one of the world's largest manufacturers of interconnect products. Supplier C became the supplier of backplanes to ATC for the F-22 radar through a recent acquisition of the defense portion of Interconnect Corporation[7]. Whereas Interconnect Corporation's market base was only about 2% defense-related, Supplier C derives about 40%-50% of its revenues from military customers. The backplanes produced for the F-22 radar represent between $200,000 and $1.5 million in annual revenues (depending on the size of annual lots). This is a relatively small fraction of both companies' total sales. It should be kept in mind that much of the discussion below relates to historical perspectives of employees as members of the Interconnect Corporation organization.

The F-22 radar backplanes are large circuit boards populated with connectors, power sources, and circuit components. They essentially form the backbone of the avionics system. Most of the radar's electronic subsystems plug into this board, which acts as the "interconnect" point. The critical performance parameters in the defense aerospace industry are board size, weight, density of connectors, and connection speed. When chosen by ATC as the radar backplane supplier, Interconnect Corporation was one of only three or four companies in the country capable of producing such highly complex boards. Supplier C, formerly a major competitor, supplied the backplane's proprietary connectors. Now that the two companies have merged, they have consolidated their MRP systems and been able to save time and money through better coordination of work orders.

While ATC controlled the backplane's initial design and layout, it received input from Interconnect Corporation's engineers in making the design decisions. This helped to improve manufacturability and reduce costs. Good communication between the

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[7] Company's real name has been disguised

designer and manufacturer is important to ensure that boards have the correct connector configurations, will achieve the tolerances required, provide the right levels of power, and meet a variety of other specifications necessary for seamless integration of systems. As a result, Supplier C's engineers frequently engage in conference calls with customers, including 3 and 4-way calls that include subcomponent vendors. A major cost driver of backplane products is lead-time. The earlier customers can notify Supplier C of what orders will be coming down the pipeline, the better it can plan equipment usage to meet the expected volumes and avoid overcapacity. Early notification about production requirements often depends on the customer's ability to quickly arrive at a final design. Good communication between companies is essential for the rapid design iteration that makes this possible.

The F-22 radar backplane design has remained fairly stable since it was established several years ago. As the integration point for the rest of the radar, a major change would require redesign of all the subsystems that plug into it. Instead, changes have been limited to minor modifications such as adjusting power levels and adding faster components. The manufacturing process is capital intensive and has become fairly standardized. As a result, the potential for further cost reductions is reportedly fairly limited. Since costs essentially become fixed with the initial design, getting the design right at the beginning is critical. Those interviewed argued that the best way to further increase affordability would be through multi-year contracts. This would enable Supplier C to run larger production batches and negotiate better terms with its suppliers. Although it may be too late for the F-22, another way the customer can contain costs is through wisely choosing the components it specifies in its designs. By choosing a highly specialized component, the customer may lock Supplier C (which actually purchases the component for board assembly) into a sole-source relationship. This tends to dramatically drive up the cost of materials.

ATC maintains constant pressure on Supplier C to seek innovative improvements in its manufacturing processes and reduce prices to the extent possible by routinely soliciting bids from two or three potential competitors. This provides enough incentive to prevent

Supplier C from becoming complacent or significantly overcharging the customer. On the other hand, Supplier C has a fairly good knowledge of its competitors' capabilities and will refuse to supply its backplanes at prices it considers unreasonably low.

Despite the continual demand to reduce prices, Interconnect Corporation (and now Supplier C) has maintained a good relationship with ATC. An Supplier C sales engineer visits ATC's facility on a weekly basis to maintain contact, resolve problems, and discuss potential plans for future programs. ATC has also solicited ideas for improving its products and supplier relationships through a questionnaire sent to Interconnect Corporation and other major suppliers. These steps by both companies have provided valuable forums for exchanging ideas. In addition, Supplier C's network of regional sales engineers help it to look across its customer base and identify the industry's emerging technology demands. A strategic action committee meets regularly to discuss technology trends and new directions for the company. This helps Supplier C to focus its innovative efforts towards critical customer needs and guides its development of new manufacturing equipment to enhance production capabilities. Unfortunately, no specific examples of innovations that occurred in the F-22 radar backplane design or production were given.

7.4 SUPPLIER D

Supplier D Printed Circuit is a division of Supplier D Technologies, a large designer and manufacturer of electronic communication and propulsion products. Supplier D supplies ATC with rigid-flex circuit boards for the F-22 radar. The annual value of this contract is roughly $750,000 and represents a small but significant share of Supplier D's annual revenues. Supplier D Printed Circuit's customer base is about 60% defense-related, 30% high-tech commercial, and 10% general-commercial. The complexity of the boards it supplies to ATC is a function of the multi-layered circuitry and the incorporation of flexible connectors, which save space by allowing more inputs for a given board orientation. The boards also require specialized material coatings and must meet very tight tolerances. Only two or three other companies in the world can manufacture boards of the same complexity. Because there are so few suppliers of these boards, many of Supplier D's engineers are familiar with the capabilities of its competitors through past work experience or friends at these companies. They can often fairly accurately gauge the threat that competitors pose, which sometimes benefits Supplier D in pricing its products. On the other hand, Supplier D faces continual pressure to innovate to maintain its technological edge and market share. A major concern for Supplier D is design decisions by customers that do not play to its manufacturing strengths. For this reason, it is important that Supplier D both anticipate customers' future manufacturing needs and work closely with them to influence the technology paths they choose.

Interviewees identified several barriers that they believe retard technological innovation. The first is lack of R&D funding at major aerospace companies in recent years. Interviewees argued that because the major contractors do less basic research, they are less inclined to accept new ideas from suppliers without extensive data to support those ideas. However, subtier suppliers rarely have the resources to conduct the detailed research necessary. As a result, many innovative ideas are left unexplored due to risk aversion and funding scarcity. Furthermore, many customers do not place the same emphasis on developing and transferring technology to suppliers as in the past. Instead, there has been a tendency to focus exclusively on "core competencies" and leave technology development in other areas to suppliers. It is not evident, however, that suppliers are compensating for this shift in customer behavior by increasing their own research activities. In fact, the opposite may be true. As suppliers are under increasing pressure to reduce costs, they may actually decrease funding for basic research. Those interviewed felt that R&D was increasingly being driven by efforts to solve problems on current designs rather than looking ahead for new technologies. While the US government offers some funding for research through the DARPA and other grants, Supplier D rarely taps this source. The time required to write the grants, generate the necessary data, and wait for the review process to be completed, is too long and requires resources that Supplier D doesn't have in the current business climate. Many of the grants require suppliers to demonstrate that the research will have an immediate payoff exceeding the expense, which is often uncertain and difficult to prove. As a result, innovation in the defense aerospace industry suffers from insufficient research across the supplier base.

Secondly, those interviewed noted that defense aerospace suppliers are rarely measured by their ability to innovate. Instead, companies are often deterred from this goal by continued adherence to military specs, many of which are considered outdated or superfluous. Unlike commercial industry, the defense sector has had difficulty transitioning to a uniform, new set of standards that are more appropriate for today's technology environment. Often designers reference old military specs simply because they are uncertain about what specs are really appropriate. In addition, military specs are often excessively complicated and lengthy and should be streamlined. For example, engineers cited one assembly drawing that contains 48 pages of specs (as opposed to the one or two pages common in commercial industry).

The time and cost to re-qualify designs also discourages improvements that increase quality and reduce cost. The boards Supplier D supplies to ATC are particularly difficult to build in volume and yields are very poor. Although the design could be significantly improved, changes have not been made partly due to re-qualification requirements. One reason that re-qualification poses a bigger obstacle in the defense sector, compared with commercial industry, is that re-qualification by similarity is rarely permitted. Even if a substitute component or alternative manufacturing process is very similar to the old one, the part must be fully retested before receiving approval.

Another factor that discourages improvement of older designs is lack of technical support from the customer to approve changes. In many cases, Supplier D is building 20-years old boards using very inefficient processes. Meanwhile, the engineers knowledgeable about such boards at the customer company have long since moved on to other projects. The buyers who remain simply treat the boards as commodity items, since they do not have the technical expertise to evaluate design modifications. Furthermore, the time and expense required to go through a material review board and other procedures often sidelines ideas upon reaching the customer. In the past, major customers retained teams of sustaining engineers, whose job it was to clean up old designs and provide approval for changes suggested by suppliers. Most companies have recently cut back or eliminated such engineering groups in an effort to reduce overhead. Yet, the experience of Supplier D engineers suggests that in reality its customers are losing more than they save by failing to implement design updates and improvements.

Supplier D's relationship with ATC has become much more collaborative in the past five years. This has significantly aided in the design of newer boards for more recent programs. Unfortunately, the increased collaboration came a little too late for the F-22. Supplier D engineers felt the manufacturability of F-22 radar boards would have been better had ATC discussed its design objectives more openly in early phases of the program, before the design became fixed. Nevertheless, ATC was characterized as being very receptive to recommendations for improvement. Customers' design decisions dramatically impact board cost. Failure to consult the supplier's engineers (such as in the case of Supplier D) during the design process can result in extremely expensive and difficult to manufacture boards. ATC has partnered with Supplier D to overcome the design-manufacturing disconnect by hiring Supplier D staff to visit its facility and give design seminars. This has greatly benefited ATC's board designers and increased communication between the two companies.

It was noted that Supplier D's relationship with ATC on the F-22 program has been especially good in recent years. This was attributed to an exceptionally good relationship between Supplier D's program manager and his counterpart at the customer customer. Engineers from the two companies talk on the phone and visit each other's facilities frequently to discuss technical issues. This has helped to solve many of the problems that have arisen. For example, when Supplier D was recently experiencing difficulties with one of its test fixtures, ATC engineers came and quickly identified a solution.

Those interviewed felt that contract negotiations with ATC typically went smoothly, although the F-22 program has not initiated collaborative cost reduction incentives with Supplier D. It has negotiated yearly fixed price contracts with the customer, but does not stand to gain significantly from achieving cost savings. Those interviewed argued that far more potential for cost reduction lies with the program's bureaucracy and hidden administrative expenses than with better technology. They noted that Supplier D's ability to reduce costs depends heavily on customer design changes to improve the product's manufacturability. They also suggested that considerable savings could be derived from multi-year contracting.

Interviewees have not witnessed a willingness by customers to share in investment projects. Customers generally want the supplier to conduct extensive testing and prove that significant savings will occur before supporting ideas. The process typically takes a long time and requires the suppliers to spend a considerable amount of money upfront, which discourages suppliers from undertaking investment initiatives. ATC has discussed the possibility of conducting lean training exercises at Supplier D. However, interviewees were skeptical of the effectiveness of additional lean training, having already been through many rounds of TQM, JIT, 6 sigma, 7,9-steps, and other programs.

8 SUBTIER SUPPLIERS TO BAE SYSTEMS

8.1 SUPPLIER E

Supplier E produces a small, direct digital synthesizer (DDS) module used in the F-22's EW suite. The module takes an input clock frequency and synthesizes a range of output frequencies. The DDS supplied to BAE SYSTEMS is a customized version of Supplier E's standard catalogue STEL-2373B module, shown in Figure 8.1. This standard module is used in a wide range of both military and commercial applications.

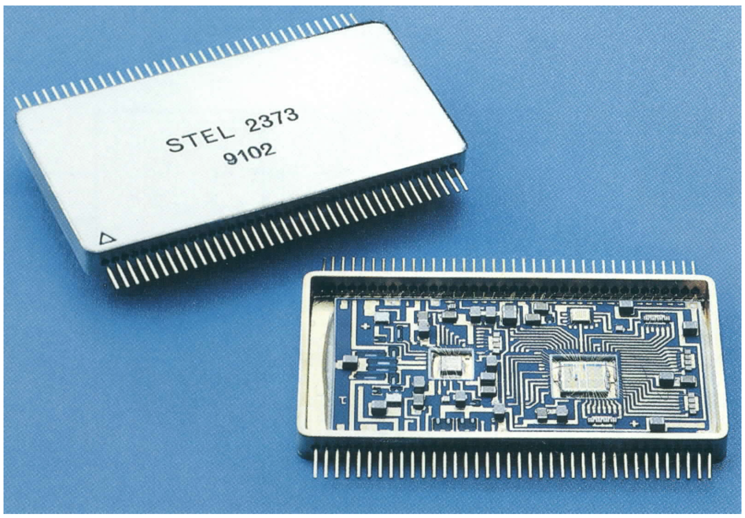

Figure 8.1 – Direct Digital Synthesizer Module for EW Suite

The modification of the standard STEL-2373B module was accomplished by integrating translators into the module package that convert TTL transistor logic into ECL transistor logic. This modification eliminated the need for a separate TTL to ECL translator card, thereby enabling BAE SYSTEMS to save space in the EW suite it builds for the F-22. In addition, the DDS must be capable of higher than normal clock speeds. The standard catalogue 2373B module is rated for a maximum clock speed of 800 MHz. To facilitate integration with other EW electronics and achieve certain performance attributes, BAE SYSTEMS needed the clock to run at 875 MHz. To meet this requirement Supplier E tests all the modules it produces and picks the ones that turn out to be capable of running at this faster rate. This causes low yield rates and increases the cost of the item.

Supplier E was chosen as an F-22 supplier because it has been able to achieve exceptionally high synthesizer performance while packaging it into a very small format. The heart of the module is a proprietary numerically-controlled oscillator (NCO) chip, which Supplier E has designed but which it has outsourced to Triquent Semiconductor to produce. However, Triquent recently announced that it has decided to upgrade its equipment and processes and would, as a result, discontinue the production of the NCO. In response, BAE SYSTEMS has made an advance buy of about 300 NCOs (enough for about 100 planes) from Triquent so that Supplier E could continue supplying the DDS modules for upcoming production lots. Meanwhile, Supplier E itself faces an important decision as to whether it should redesign the NCO. This, in turn, raises additional questions and complications, particularly since most of Supplier E's products depend on the same NCO. One option would be to ask Triquent to develop a line to produce the same NCO using new processes, which would probably be fairly costly. Alternatively, Supplier E could redesign the NCO and consider other fabrication sources that might be cheaper. However, a redesign would likely require changing the entire module layout and switching pin positions. This would impact a large number of Supplier E's customers, which have already designed their systems to accommodate the particular pin configuration. Therefore, Supplier E must balance the desire to accommodate customers by retaining design continuity and the need to think strategically about its future product lines, which depend on a cost -effective source of critical components and continual technological advancement.

BAE SYSTEMS paid for a portion of the TTL to ECL modification on the F-22 module. However, Supplier E generally funds development work itself in order to ensure that it retains all rights to proprietary technology. This is particularly true if it believes the new technology will broaden its technology portfolio and have a wide range of applications beyond a specific customer's needs. On the F-22 program, Supplier E does not face intense competition from other suppliers because few other companies can produce synthesizers that offer the same performance and clock-speed characteristics. Furthermore, now that BAE SYSTEMS has designed its system around a particular module's specifications, the costs of switching to another module would probably be very high. Despite this dependency, BAE SYSTEMS has always been pleased with Supplier E's product and has remained a steady customer, both on the F-22 and on other programs. In fact, BAE SYSTEMS (counting its many different programs and sectors) is Supplier E's largest customer.

Supplier E's revenue base is currently about 70% government/defense and 30% commercial. However, it has been closer to 50/50 government vs. commercial in the past, and this percentage has varied with swings in the commercial electronics market. F-22 related business represents a fairly small portion of total sales. Although the potential for future business is fairly good, considering spares and upgrades, there is no upfront commitment to the long term. The commercial side also tends to be uncertain in the long term, but in contrast, the customer is often willing to buy much larger quantities at the outset. For example, first-time commercial customers often sign contracts for 300 or more synthesizer units at a time, while defense customers often only want lots of 30. Defense business can be aptly described as a courting relationship. More important than the direct revenue derived from the F-22 program is the relationship that it helps Supplier E to maintain and strengthen with BAE SYSTEMS. Supplier E hopes that its involvement in the F-22 program will provide entry into the JSF program and will also generate recognition for itself among other government customers as a reputable supplier.

Because the item Supplier E supplies to BAE SYSTEMS is essentially a catalogue product (albeit with some modifications), extensive collaboration in design and production has not been necessary. Those interviewed reported that communication with the customer was fairly good. Although Supplier E does not have much information about how their product integrates into the larger EW system and would be curious to know more about this, it is not evident that such knowledge would lead to significant product improvements. Negotiations with the customer have been pretty straightforward as well, since Supplier E uses published catalog pricing for its products. The primary focus has been the level of volume discount to award when order size is just below the normal price breakpoint (e.g. a unit price reduction normally occurs at 100 units, while the customer only wants 98 units). The contracts are negotiated yearly for the number of modules BAE SYSTEMS needs for upcoming production lots. For example, the latest contract (for PRTV and Lot 1) involved an order of 98 units at a price of approximately $5000 each. A delivery schedule of 7 pieces/month was agreed upon. This delivery rate balanced Supplier E's desire to deliver and receive payment as quickly as possible and BAE SYSTEMS's desire to stretch out the schedule even longer. Interestingly, government contracting regulations were not cited as a hassle or deterrent to business. In fact, Supplier E reported that in many cases governmental contracts are less complicated that commercial versions because the procedures and provisions are fairly standardized. Although Supplier E must provide more extensive data and test information to BAE SYSTEMS, this extra cost is simply tacked on to the catalog price and is not a major source of contention.

In terms of technological innovation, Supplier E noted that its primary incentive is the potential for increasing market demand. With the current 2373 synthesizer product, the company faces a fairly closed market. Supplier E would ideally like to further enhance the product's performance in order to attract outside interest and increase its revenue base. Its engineers are constantly looking for ways to accomplish this. A deterrent to product innovation, however, is current customers' desire for design stability. Any design improvements that require changes in module layout or function would generally be unattractive to them. On the F-22 program, Supplier E has not requested funding from BAE SYSTEMS to improve the product's performance. Supplier E has reportedly made such requests on other programs, but BAE SYSTEMS has generally been unwilling because the money for such initiatives reportedly must come from BAE SYSTEMS's customer. Even if BAE SYSTEMS did make such an offer, however, it is unlikely that Supplier E would accept it unless it would be assured of receiving all of the rights to any new technology. Interviewees did note the importance of communication with customers regarding their long-term technology goals and projected performance needs. This is especially true during a time when the company is in the process of considering an NCO redesign. Communication of goals helps Supplier E to identify the critical attributes that it will attempt to incorporate into future products. The more customers it can attract and satisfy, the cheaper the product will become for everyone.

The potential for process improvements on the synthesizer is also fairly low. The module consists of only a few critical components and much of the actual manufacturing is outsourced to large electronics fabrication houses. Because production volumes are low, investment in new process equipment (which is typically very expensive) would not pay off, even if the customer were willing to share in the expense. It was noted that one effective motivator of process innovation in the company as a whole is ISO9000 auditing. In order to receive ISO9000 certification, managers are forced to evaluate operations on a regular basis in search of ways to improve efficiencies.

The biggest potential for cost savings on the F-22 program seems to lie in increasing order quantities through multi-year contracting, as well as combining orders for the same synthesizer across the various BAE SYSTEMS programs that use it. Up till now, this has only been done on a small scale. BAE SYSTEMS reportedly realized a fair amount of savings in the last contract simply by combining Lot 1 and PRTV orders. Larger orders reduce cost by enabling Supplier E to purchase components in bulk in advance from its suppliers and avoid increases in material costs. Supplier E reports that the prices of many of the materials and components used in its products have been steadily going up rather than decreasing over time as one might expect. Consequently, Supplier E is often able to save customers money by purchasing them in advance if it is assured of future sales. Mere speculation by the customer about the size of the F-22 contracts it will receive in the future, however, provides neither the compensation nor the incentive for Supplier E to reduce the price of its product.

8.2 SUPPLIER F

Supplier F supplies the EW suite's logarithmic amplifier (LA) to BAE SYSTEMS. This is an RF amplifier in the UHF range, which goes into the EW's channelizer and provides a measurement of signal strength. The channelizer consists of 56 individual (but nearly identical) pieces or modules, which break the frequency spectrum into chunks to allow viewing of frequency characteristics for signal identification. Supplier F began the initial prototype work for the LA about 9 years ago. It recently began contract work to produce the LA for production Lots 1 & 2. In the interim period between the recent contract agreements and early prototyping, Supplier F lost the F-22 business to another competitor. When the competitor failed to perform to expectations a couple years ago, BAE SYSTEMS turned back to Supplier F to provide the LA. By then, a number of the specifications had changed over the course of EMD and Supplier F had to make some modifications to its old design. The company is currently setting up its production line for a full-scale production rate of 3 ship sets of amplifiers per month. This rate is faster than necessary for early phases of F-22 production, but the company is assuming that the program will eventually reach its scheduled full production rate of 36 planes per year.

The critical technology within the LA modules is an application-specific integrated circuit (ASIC), which Supplier F developed internally and outsources to an IC vendor. The circuitry was designed specifically for the F-22 platform. The housing of the modules is also unique and incorporating all of the electronics into the necessary form factor represented quite a mechanical challenge. In general, Supplier F describes itself less as a developer of innovative electronics than an innovator in electronics packaging. Its specialty is taking current technology and figuring out how to integrate, package, and manufacture it into a wide range of complex, low-volume, electronics products. Correspondingly, the company owns a large amount of specialized machinery and test equipment. Many of the production processes are fairly labor intensive. It is heavily dependent on defense business, which represents between 60% and 80% of annual sales. This is a decline from several years ago when defense was as much as 95%. The current company consists of a conglomeration of 5 smaller, formerly independent suppliers and generates annual sales of about $120 million. F-22-related business is a fairly small percentage (~5%) of this. However, interviewees noted the program's importance from the standpoint of maintaining defense relationships and industry visibility, as well as the long-term business assurance that being on a major program provides.

Supplier F is currently under a fixed price contract to supply the LA to BAE SYSTEMS. Those interviewed reported that the company is currently losing money on this contract. They hope that by making some changes to the manufacturing process they can reverse this. The contract price Supplier F agreed to, after gaining back the business following the dormant period in EMD, turned out to be less than the cost for Supplier F to actually produce the product. This was partly due to unexpected design changes it had to make to comply with new specifications that had evolved over the course EMD, with which Supplier F was not familiar. In one case, managers at Supplier F overlooked a new requirement included in the revised contract, which ended up being very costly to meet. Innovation in product performance was virtually mandated by the increasing complexity of specifications being flowed down from the customer over the last few years. Supplier F has had trouble just achieving the degree of functionality the customer desires, much less figuring out how to make the functionality affordable. Supplier F's experience in designing products for new programs (like the F-22) has been that the customer would first look at what hardware is generally available on the market, compare it with the performance objectives, and develop a rough "straw-man" list of specifications. The customer would then discuss possibilities and negotiate with the supplier until the two parties eventually arrive at a final agreement on the actual list of specifications. As the program evolves, however, the customer would often request additions or modifications to this list to solve unforeseen integration problems that arise. Based on past experience, such changes can significantly complicate the supplier's efforts.

The company has recently begun redesigning its LA manufacturing system using lean principles in an effort order to cut production costs. It is expecting to achieve considerable savings through process improvements. This will hopefully enable it to continue supplying BAE SYSTEMS at the current price while increasing Supplier F's profitability. Although Supplier F has not received any lean training from BAE SYSTEMS, it has implemented a number of lean practices and has begun holding ***kaizen*** events on its own. The impetus for much of this improvement has been the Vice President of Operations, who participated in a lean training course held by the University of Kentucky and Toyota when he was formerly employed by Lockheed Martin. Supplier F has not received funding towards investment in new process equipment. However, interviewees held the view that there is no "silver-bullet" machinery or equipment that would dramatically improve its efficiency. Rather, its focus is on investing in duplicates of common process equipment that will simplify the manufacturing flow. Rather than pursuing extensive automation, the company sees greater potential in concentrating on manual lean practices.

The technical complexity of the product Supplier F supplies has required extensive communication between companies. This has sometimes been a challenge. Typically, after Supplier F has received a list of specifications and gone off to design and build the product, unforeseen complications or issues have arisen. Its engineers must then locate the right person at BAE SYSTEMS (often the systems engineer) to discuss and resolve the problem. This often requires going through several layers in the customer's organization before finally connecting with the person who has the knowledge and authority to approve solutions. The process can be time-consuming and frustrating. Interviewees attributed this partly to reduced staffing and increased workload of key technical personnel at the customer in recent years. It was their perception that the strong emphasis on cost reduction across the industry has resulted in much greater responsibilities and pressure on the personnel who remain. No major changes were cited in Supplier F's relationship with BAE SYSTEMS from a global standpoint over the past 10 years. Ironically, however, one of those interviewed captured a broader perception of those present in describing what he saw as "a growing interest in cooperation, but fewer resources to actually do so." The interviewees also reported a positive trend in the removal of many onerous defense regulations, data reporting, and inspection requirements that have burdened suppliers. This has permitted Supplier F to focus more on performance rather than on red tape. Nevertheless, there still appears to be room for improvement in this area, particularly in contracts directly between Supplier F and the government (for items such as spare parts).

Another potential communication disconnect involves the extensive list of terms and specifications that surround contracts for a complex product. The contract for the LA has undergone a number of revisions over the course of the program. The revisions are very lengthy documents describing in detail the latest contract conditions and functionality requirements for Supplier F's product. It often takes considerable amounts of time for Supplier F personnel to identify and evaluate the cost impact of all the changes from one revision to the next. There is danger, as mentioned above, that they will overlook important variations in the requirements and therefore underestimate cost. It was suggested that the customer could help by more clearly identifying and discussing desired changes in each revision.

Supplier F's engineers do not have much knowledge about how their product integrates into the channelizer and other parts of the EW system. Interviewees felt that it may have been a little easier to sort out some of the past technical difficulties if they knew a little more about what was going on at higher system levels. However, BAE SYSTEMS's desire to prevent diffusion of proprietary information about its design sometimes presents a barrier to greater system visibility. Getting past security clearances has also sometimes made it more difficult for Supplier F engineers to gain access to the right people to discuss design tradeoffs.

Interviewees felt that the customer-supplier relationship could be made even better by reducing the number of discrepancies over what qualifies as acceptable product performance. It was reported that frequently Supplier F designs its product, tests it for performance, and ships it to BAE SYSTEMS, after which it receives calls from BAE SYSTEMS claiming that the product does not function properly. The product is then returned to Supplier F and a team of engineers are pulled away from other work to examine and retest it. After Supplier F retests and determines the product does indeed function as specified, BAE SYSTEMS finds out that a change in another part of its system was causing the problem. Unfortunately, this whole process poses a distraction, consumes a lot of time, and creates delays. It can strain an otherwise good relationship as frustrations mount and accusations are exchanged over who should bear the blame. This illustrates the effect of the extremely tight design margins which the program faces, and speaks to the importance of carefully considering the interactions between components in the system. It also indicates the need for even closer communication to allow suppliers and the customer to maximize collaborative efforts and quickly find solutions to integration problems. Perhaps a focused examination of the extended supply chain and the capabilities and characteristics of its members would be useful. This could help to tighten the linkages, identify interdependencies, and increase coordination and teamwork. It was noted that this type of supply chain mapping, generally known as supplier value stream analysis, has occurred a few times in the past, and interviewees found the process to be very beneficial each time, fostering greater synergy with the suppliers. Therefore, they recommended conducting such exercises more often and believed it would be a valuable learning experience for both Supplier F and the customer.

There are no strong contractual incentives for Supplier F to innovate. The defense establishment is reportedly very conservative when it comes to new contracting practices and incentive mechanisms. For the most part, attitudes have not changed much and contracts are primarily characterized by continuous pressure on the supplier to reduce cost to the maximum extent possible. In fact, once the supplier has met the customer's specifications (which has been challenging and lengthy process on the F-22), further product innovation is effectively discouraged by requalification requirements. Design changes (even if done to enhance performance beyond what is required) must be accompanied by extensive requalification measures, which are both expensive and time-consuming. Even process innovations that significantly alter manufacturing or assembly methods can necessitate requalification. This tends to limit innovation to minor producibility improvements. In addition, there is constant pressure in the early phases of large, complex programs to quickly arrive at a stable baseline design so that uniform production may begin. Then once production has begun, the primary goal becomes meeting aggressive production schedules and avoiding delays at all costs. There is little time for engineers to shift gears and consider improvement possibilities. This creates an environment that is not conducive to continuous product or process innovation. It was felt that major innovations must be pursued at the prime contractor level because most suppliers do not possess the resources necessary to devote to such efforts.

Supplier F faces limited competition from other suppliers for F-22 business, particularly now that they have won early production contracts. Supplier F serves a small niche market, and only two or three other suppliers in the country possess similar capabilities. Now that its design is on the airplane, Supplier F is pretty much locked into future contracts. However, it is understood that taking the customer hostage would be a poor strategy, even if it might yield short-term gains. Because Supplier F depends heavily on BAE SYSTEMS (for a large number of contracts) and defense business in general, marring its reputation by playing “hardball” would be highly detrimental to its long-term business prospects. In fact, despite losing money on the current contract, Supplier F has reportedly refrained from going to the customer to ask for more funding. Instead, it has decided to first examine its own practices in search of ways to minimize cost and help achieve program affordability goals.

Those interviewed felt that the F-22 program would derive considerable benefit from establishing multi-year contracts with suppliers. In addition to providing greater incentive for suppliers to improve, they saw this as an important prerequisite for making many strategic, long-term investments. Supplier F would be much more willing to make equipment investments which would reduce production costs. Multi-year contracts would also help Supplier F from a materials procurement standpoint, because it could justify committing to one vendor and devoting resources to develop that source. Instead, procurement personnel currently spend a lot of time shopping around for alternative sources whenever current suppliers perform poorly. The duration of contracts also impacts decisions about employee hiring and training. Without longer term commitments, Supplier F is less likely to invest in finding and hiring top-notch engineering talent for its projects. Nor will it commit resources to training to improve employees' toolsets. Such a trend among suppliers can have a major impact on innovation across the entire industry.

8.3 SUPPLIER G

Supplier G supplies a series of syntactic foams to BAE SYSTEMS for use in the EW system. The composition and precise application of these foams is proprietary, but they are lightweight and tuned to specific electrical properties. The foam is delivered as an uncured loose material stored at low temperatures, with a consistency similar to snow. BAE SYSTEMS packs it into molds, and at elevated temperature it hardens. Supplier G's operations involve taking in raw materials, specially mixing them, testing for desired electrical properties, and then supplying the foam in zip-lock bags inside Mil-Spec Vapor Barrier Containers to the customer. It is important for Supplier G to coordinate its production with BAE SYSTEMS because the foam has a limited shelf life and cannot be stored for long periods of time. Likewise, Supplier G must coordinate the delivery of a critical material from one of its own suppliers, which requires storage in dry ice. A delay in transportation of its supplier's material could result in the material becoming useless. In turn, this could delay Supplier G's shipments to BAE SYSTEMS. Since it must closely coordinate production with BAE SYSTEMS and produce in small lots, it cannot benefit from volume discounts by buying ahead. As a result, Supplier G reports that although multi-year contracting might have some benefits, it probably would not be a major contributor to cost reduction.

Supplier G's foams are used primarily in aerospace applications. The commercial-military business composition has varied considerably in recent years. Five years ago, the company's revenues were 75% commercial, 25% defense. Six months ago that ratio had flipped, and then recently the company won several large defense contracts and the ratio has tilted back slightly in favor of defense. The F-22 program, representing about 10-15% of total revenues, is an important but not critical source of business. The four types of foam Supplier G provides to BAE SYSTEMS for the F-22 were uniquely developed for the program and tuned specifically for microwave properties and energy attenuation properties required by the EW system. Due to their proprietary nature, these particular grades cannot be sold to other customers. Supplier G is a small supplier with about 60 employees, but has a very high overhead in the form of security measures. Employees must go through an extensive process to receive security clearances, technical information must be stored in safes, and rooms must be equipped with sound proofing and secure phones. It was also noted that considerably more documentation and reporting requirements accompany government contracts, making military contracts more complex and time-consuming.

Supplier G is the largest player in the aerospace grade electrical syntactic foam market. Security requirements coupled with the technological complexity of the product present significant barriers to entry for competitors. However, several other companies are catching up and could eventually pose threats to Supplier G's market position. This will especially be true if contracts continue becoming less classified, enabling more competitors to enter the market. Supplier G funded and conducted the R&D for the F-22 grades of foam itself. It generally prefers to internally fund development efforts to retain all intellectual property rights to the technology, and is very protective of its technical information and processes.

Engineers described the product development process over the course of the program as an iterative process, with requirements from the customer becoming increasingly complex and difficult to achieve. As product specifications have continually tightened and demand for more extensive testing has increased, the design margin has become very small. Throughout this process, engineers at Supplier G and BAE SYSTEMS have interacted frequently. Supplier G has been very open in sharing information with the customer, including even disclosing the components in the product. In turn, engineers from BAE SYSTEMS have visited Supplier G to help with manufacturing processes. In addition, Supplier G has been working closely with one of its raw materials suppliers, which has also been surprisingly open in discussing its product, despite the fact that Supplier G is also a potential competitor. Close collaboration across the supply chain has occurred because its members recognized the critical need to improve specific areas of the production process to meet stringent program goals. Although those interviewed viewed Supplier G's relationship with BAE SYSTEMS as generally positive, they noted that sometimes the company has a "large-company mentality" in dealing with smaller suppliers. BAE SYSTEMS does not always understand the challenges facing employees of smaller companies, who often must wear several hats and attend to many different responsibilities.

A couple years ago, Supplier G held an extensive cost review session with the customer. Through this effort, the companies were able to jointly identify some cost-savings through elimination of a few testing procedures. However, the largest opportunity for savings involved shifting to internal production a critical material that was being purchased from one of Supplier G's suppliers. This supplier's material was tailored for the F-22 program, but Supplier G was also capable of producing an alternative material with multiple applications and with equal or better properties. Nevertheless, BAE SYSTEMS decided not to pursue this option. Those interviewed suspected that this was due to the uncertainty and cost associated with requalifying the foam with a slightly different composition. In fact, the customer may have been unsure what tests would even be required to fully ensure the foam was acceptable and would not alter the system's performance.

Supplier G reports that its contract person deals daily with buyers at BAE SYSTEMS discussing contract options and their impact on cost. A good dialogue has been established with mutual understanding of each other's needs and limitations. This is important because changes in requirements by BAE SYSTEMS can dramatically affect Supplier G's price. For example, Supplier G currently has its machine capacities set to produce enough foam in each batch to test a portion and ship the rest to BAE SYSTEMS in the right volume. If the required volume per plane increases considerably, costs would increase because Supplier G would have to make major adjustments to its production capacity to increase batch size. Increasing performance requirements can also significantly reduce yields, which has been a major problem for Supplier G and BAE SYSTEMS on the F-22 program. In some cases, requirement changes impact Supplier G's suppliers and reduce their yields. This frustrates the suppliers and leads them to request renegotiation of their contracts with Supplier G. The whole process has been such as hassle for some suppliers that they no longer want Supplier G's business. Supplier G's engineers have spent a significant amount of time testing the materials, playing with the recipe, and calibrating the processes. The company is not convinced that it has recouped all of the expense it has put into the program. Nevertheless, Supplier G remains involved in the interest of maintaining long-term relationships and protecting its position in the industry. It recognizes that accepting lower profits on some contracts may occasionally be necessary in the defense business in order to preserve and enhance its future business prospects.

8.4 SUPPLIER H

Supplier H is a small supplier specializing to surface acoustic wave (SAW) devices. Over 80% of its business is low-volume, technologically-advanced specialty items for the defense industry. Therefore, engineering labor comprises a large portion of its cost structure. It supplies BAE SYSTEMS with seven separate part numbers for the F-22, with a shipset requiring multiples of each for a total of 34 pieces per plane. The parts are manufactured by coating glass wafers with metal, dicing and packaging them into components, and packaging the components, along with other electronics, into hermetically sealed modules. These modules serve as filters and delay lines for signal processing within the EW suite.

Supplier H won the contract to develop and manufacture its products for the F-22 in 1991, after a competition against another competitor. BAE SYSTEMS gave Supplier H a design envelope (shape and weight of the module package) along with detailed specifications about the signal inputs its SAW devices would receive and the types of output that should be produced as a result. Supplier H engineers then spent three years developing these devices and qualifying their designs. During this process, specifications that were particularly difficult to meet were discussed with BAE SYSTEMS and specification tradeoff opportunities were identified. The development work was technically funded by Lockheed Martin's Sanders unit (which BAE SYSTEMS has since acquired). However, the costs well exceeded the funding allotted to the task, so Supplier H effectively funded a portion itself. Although Supplier H faced a number of technical obstacles in achieving the performance desired by its customer, it was able to overcome most of them prior to the initial qualification and freezing of the design. This had the important benefit of enabling it to move directly from its prototype design into a production version, rather than going through a series of changes and requalifications. A key to controlling costs was strong emphasis on design for manufacturability. Because low yields and rework can dramatically increase costs, designers strove to assure the producibility of its work.

The F-22 program represents a significant share of Supplier H's revenues and is of major importance to the company. Recent contracts have been estimated at around $3 million per lot. The comparatively high volumes (compared to Supplier H's other contracts) give Supplier H the opportunity to become more of a manufacturer rather than a job shop for SAW devices. Its lack of experience with volume manufacturing initially concerned the customer, and still remains a point of uncertainty. However, Supplier H is one of only two or three companies in the world possessing the technical capabilities BAE SYSTEMS requires. BAE SYSTEMS became even more dependent on it after one of its major competitors merged with another company and decided to exit the defense business. BAE SYSTEMS has since recognized Supplier H as a sole-source supplier for the F-22 program. Nevertheless, BAE SYSTEMS appears to retain leverage in negotiating prices as a result of Supplier H's financial dependency. Supplier H reported that the customer has continually exerted strong pressure for price reductions. In an early production lot, Supplier H grossly underestimated its costs and had to increase its prices in a subsequent lot by 60%. Naturally, this was shocking to BAE SYSTEMS and it refused to fully recognize such an extreme increase. Supplier H remains uncertain whether it will be able to meet the current cost objectives for upcoming Lots 2 and 3.

Joint efforts with BAE SYSTEMS are reportedly critical to further reducing cost. Lean training initiatives have been very effective in helping Supplier H's employees to identify ways to eliminate waste and think more creatively about improving their processes. A team from BAE SYSTEMS recently visited Supplier H's facility and taught lean principles to nearly every employee in the company. This is particularly important as Supplier H begins to ramp up its manufacturing operations to meet the demands of the F-22 program.

Due to its small size, Supplier H has a limited pool of capital from which to finance its operations and improvement efforts. In the development phase, for example, it was important to have contract payments based on the completion of specific milestones rather than a lump sum payment at the end. By matching the funding with the engineering effort, it was able to ensure that it had the funds to proceed. Likewise, when Supplier H identifies opportunities for improvement requiring significant capital outlays, it generally depends on the support of its customer. For example, engineers recently discovered that a particular amplifier in one of the modules is a major source of unreliability. Supplier H believes it could recognize considerable long-term savings by asking one of its own suppliers to redesign the amplifier. However, this would cost about $25,000 for the supplier's effort and an additional $25,000 for Supplier H to redesign the module. Supplier H has submitted a proposal asking BAE SYSTEMS to fund part of the total and is hopeful that it will receive the requested funding. Supplier H would also like to send its employees who manually build many of the modules to a training program to increase their skill. By teaching them better methods of identifying defects and bonding components, such a training program could immediately improve yields and increase reliability. However, the training would cost approximately $20,000. While Supplier H has suggested it as a cost saving initiative, BAE SYSTEMS has resisted contributing funds, arguing that it should not act as Supplier H's "banker."

Despite the competitive nature of contract negotiations, those interviewed rated the overall relationship between Supplier H and BAE SYSTEMS as "extremely good".

Characterized as highly collaborative, it features frequent communications between engineers and managers at both companies. Supplier H has frequently asked for assistance to improve and BAE SYSTEMS has always been quick to respond and willing to share its expertise. BAE SYSTEMS has routinely sent teams of engineers to visit the Supplier H's facility and make recommendations for improvement. For example, BAE SYSTEMS material experts have helped Supplier H identify better adhesives for use in its bonding processes. Supplier H engineers can challenge BAE SYSTEMS's specifications and testing requirements for the products it provides.

Supplier H organizes the steady exchange of information with BAE SYSTEMS by requiring all communication to be channeled through the program manager. When the program manager first enacted this rule several years ago, it required a difficult adjustment for his engineers. It meant they had less freedom to call up their counterparts at BAE SYSTEMS whenever they wanted to recommend a change. However, he found that it greatly improved the productivity of the communication by ensuring that everyone understood and approved of the ideas being exchanged. Engineers at Supplier H routinely meet together to jointly discuss proposed improvements and confirm that they make sense before bringing them before the customer. This helps to prevent surprises and eliminate short-sighted solutions. The program manager also maintains a record of past suggestions and the outcome of attempts to implement them to avoid repeating mistakes.

Because Supplier H works so closely with BAE SYSTEMS, BAE SYSTEMS has great insight into its cost structure. In order to justify its price to the customer (which is often shocked that the parts are so expensive), Supplier H generally lays out its cost structure in detail. This facilitates trust by demonstrating that Supplier H is not making excessive profits at the expense of its customer. In some cases, it also helps BAE SYSTEMS to target its assistance by revealing areas most in need of improvement. On the other hand, the customer must be careful in assuming that it thoroughly understands the supplier's business and dictating changes that miss the real problem.

9 ANALYSIS

9.1 INTRODUCTION

This chapter explores the major themes that emerge from the preceding case studies. It begins by discussing how the nature of the F-22 program has affected the types of innovation that have occurred. It then examines the practices and the characteristics of the observed relationships that were found to be the key drivers and enablers of supplier-based innovation. The major barriers to supplier-based innovation that were encountered are also described, with an eye towards ways of overcoming them or minimizing their impact where possible. The final sections of this chapter address the important role that the US government and defense customers play in nurturing the innovative potential of aerospace supplier networks. Based on lessons drawn from this study, suggestions are offered for further steps that defense aerospace companies and government customers can take to foster greater innovation across their supplier networks.

The F-22 is perhaps the most technologically advanced aircraft ever built. Its impressive performance has been derived from the many technological innovations achieved by various companies participating in this program. Much of the major product innovation occurred in the early years of design and development, whereas more recent years have seen an emphasis on refining the design, improving production processes, and increasing affordability. The focus of the case studies in this research was not to determine the sources of specific innovations that occurred on the F-22. Rather, the case studies have served to highlight the nature of supplier relationships and their impact on supplier behavior and innovative potential. The interfaces between customers and suppliers were studied to gain insight into characteristics and practices that tend to support and stimulate supplier-based innovations. The findings that follow should be considered in this light.

9.2 INFLUENCE OF THE F-22 PROGRAM ENVIRONMENT ON INNOVATION

9.2.1 "Specified" Innovation

The structure, goals, and management of the F-22 program have impacted the process of innovation in unique ways. One way suppliers have been driven to innovate is through the imposition of extremely challenging product specifications by customers. These requirements have been flowed down from the prime contractor to major subcontractors to subtier suppliers in an effort to meet aggressive performance goals established by the end user – the Air Force. The performance goals were exceptionally ambitious (even in the context of defense acquisition programs that have typically "stretched" the technology envelope), and the F-22 features a highly integrated and complex avionics system. In order to achieve the F-22's impressive functionality within significant constraints on weight and space, seamless integration of a wide array of electronics and software systems from many sources was necessary. As a result, suppliers have been challenged with very tight design margins in order to ensure that their products meet the stringent performance and integration requirements. While this has demanded a high degree of technological innovation, it has also meant that innovative efforts were somewhat narrowly focused. In many cases, there were relatively few design options available for suppliers to pursue in meeting the customer's objectives. As a result, the program has experienced a high degree of what could be termed "specified innovation." Rather than suppliers independently considering various ways in which they might improve their products, customer companies have essentially dictated how and along what dimensions this would occur.

The Air Force made a wise decision on the F-22 program to use performance-based requirements and specifications where possible, rather than detailed technical specifications, to give designers more flexibility. Nevertheless, in such a highly integrated system flexibility quickly diminishes as design decisions are made at higher levels, particularly as one looks at the supply chain beyond the prime contractor and major subcontractors. Therefore, communication that extends beyond the first layer of the supply chain and taps innovative ideas residing across suppliers deeper in the chain is particularly important early in a program. Integrated design teams should include not only cross-functional team members from the prime contractor and acquisition organizations but also members from key lower tier suppliers. Otherwise, the contractor's knowledge of the technical capabilities of suppliers is derived principally through its prior experience with these suppliers or may simply be based on contractor assumptions. The contractor's knowledge or assumptions regarding the suppliers' capabilities would generally be based on previous design experience and would most likely provide a rather narrow context for innovation by suppliers. A "design it like we've done in the past" philosophy would likely overlook new capabilities and ideas of suppliers and lock them into less efficient methods of production.

9.2.2 Innovation and Differences Between Modular and Integrated Systems

The risk of severely limiting suppliers' creativity would seem to be considerably greater in cases of highly complex and integrated systems, like avionics, compared with cases involving highly modular systems. A modular system can be decomposed into separate blocks whose designs can be optimized separately as long as designers maintain specified interfaces between and among the blocks. One could consider the simple example of a ceiling fan, which might consist of blades, a motor, and a light fixture. The fan's assembler could purchase these three separate parts from different suppliers. The blade supplier could experiment with a wide variety of blade designs as long as the blade ends connected properly to the rest of the fan. Likewise, the motor supplier could pursue innovative new motor designs that were quieter or more efficient without significantly impacting the rest of the design. Highly integrated systems are different. It is much more difficult to decompose them into independent modules and outsource them to separate suppliers. Design decisions made in one part of the system often have a major impact on the design of the rest of the system. This means that the usefulness of an innovation within a particular part actually depends on the architecture of the surrounding system. Suppliers must develop most innovations "in concert" with other suppliers, rather than independently, for them to truly add value for the customer.

As a result, good communication across suppliers and between suppliers and the customer is essential when striving to develop innovative, highly integrated systems.

9.2.3 Importance of Understanding the Extended Supply Chain

Lean companies today realize that key competitive advantages stem not only from their own capabilities and the capabilities of their immediate suppliers, but from extended chains of subtier suppliers. This is particularly true in an industry such as microelectronics, which is rapidly evolving and advancing technologically. A lower-tier supplier's actions can confer major benefits or cause severe problems to customers several tiers above. Unfortunately, many companies have poor visibility into their extended supply chains and the opportunities and dangers embedded in them. As a remedy, Fine (1998) advocates supply chain mapping exercises. These exercises help firms to understand the path by which raw materials are transformed into a final product and to identify points of value creation and risk along the way.

The case studies indicate that a good map of the extended supply chain "value stream" is valuable not only in the initial stages of design, but throughout the course of a major defense program. It provides insight into critical interdependencies in the production process and helps the customer company locate opportunities for improvement. It is also a key to understanding how small changes by the customer might impact suppliers in major ways as the effects filter down the chain. During the EMD phase of the F-22 program, engineers at both the prime contractor and major suppliers have made many modifications to the initial design to remedy problems, improve performance, or reduce costs. In many cases, however, seemingly minor changes have turned out to be much more complicated as a result of the integrated nature of the product and the long chain of suppliers affected.

The syntactic foam example discussed earlier provides one example of why dependencies along the extended supply chain matter and should be understood. A map of the organizational supply chain for syntactic foam for the F-22 looks as follows:

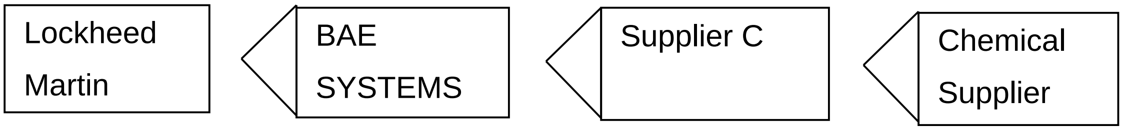

Figure 9.1 - Organizational Supply Chain for Syntactic Foam

As discussed in Chapter 7, delays in delivery or quality problems by the chemical supplier that provides a critical foam ingredient to Supplier C can easily delay the production of the foam. In turn, this delays production of the EW suite, and ultimately the entire aircraft. Going in the other direction, requests by BAE SYSTEMS for slight adjustments in the foam's properties (perhaps triggered by minor requirements changes for the EW by Lockheed Martin) often require the chemical supplier to alter the composition of its product. This alteration in composition can be costly and time-consuming. As these changes or modifications have mounted over the course of the program, the supplier has become increasingly frustrated, nearly to the point of refusing the F-22 business. Such feelings of exasperation can destroy the drive for innovation among lower-tier suppliers.

In the case of Supplier A (discussed in Chapter 7), changes in process equipment by the semiconductor company to which it outsourced one of its critical synthesizer components led to an obsolescence problem for BAE SYSTEMS. Familiarly with the supply chain is essential for identifying such problems early and developing long-range strategies to cope with them. In many cases, the most innovative design will be ones that take into account expected technology shifts and potential sources of DMS parts and find ways of avoiding or mitigating their potentially negative impacts in the future.

9.2.4 Innovation in Requirements

Innovation in requirements definition, although not typically considered under the categories of product and process innovation, has proved very important on the F-22 program. This type of innovation involves identifying and eliminating unnecessary performance and test requirements, as well as identifying more affordable approaches to meeting essential requirements. Discussion with companies revealed that a substantial portion of F-22 suppliers' costs stem from the rigorous test procedures customers generally require to verify product performance and reliability. These might include fatigue tests, ruggadization tests (submitting a product to extreme temperatures, vibration, or impact), tests of microelectronic performance characteristics, and a variety of other tests. Low tolerance for, and potentially severe consequences of, failure in the defense aerospace environment mandate stringent testing practices. In some cases, however, suppliers appear to be conducting more testing than is truly necessary to ensure the quality and reliability of their products. By carefully reexamining testing requirements they have required their suppliers to perform, customer companies have been able to identify and eliminate superfluous or ineffective tests. For example, tests that were important in early phases of development may no longer be necessary as manufacturing processes have been improved and have become standardized. In other cases, the customer realizes that certain dimensions of performance are less critical than initially expected and do not need to be confirmed through testing. In the early stages of a new program, customers often over-prescribe testing because of uncertainty about which tests are really essential. As the program progresses, customers and suppliers have the opportunity to refine the testing requirements and develop improved methods for meeting them. This often leads to significant cost savings that the suppliers can pass on to the customer. Collaborating with suppliers to streamline testing procedures and to provide relief from onerous and unnecessary testing requirements represents an important enabler of innovation that can provide major benefits to defense aerospace programs.

Along the same lines, innovation results from recognizing and eliminating performance requirements that are unnecessary or cannot be met cost-effectively. Early in the design process, customers typically impose detailed and ambitious performance requirements on suppliers. This is done to ensure that the many parts of a complex system can be integrated properly. The difficulty in achieving many of these requirements, and their importance to overall system performance, only becomes clear later in the program. In some cases, however, the original requirements are never reevaluated to determine their criticality and cost. This can result from organizational bureaucracy or from disconnects between customers and suppliers. For example, the supplier may not have visibility into the design of the larger system. As a result, it may be unaware of how various requirements for its particular part relate to higher-level performance goals and may simply accept them as fixed. On the other hand, the customer may fail to realize the extent to which particular requirements impact a supplier’s costs or perhaps even the costs borne by subtier suppliers. Awareness among suppliers at various links in the supply chain regarding the cost and essentiality of performance requirements can lead to new opportunities for value creation benefiting the program. Innovative supply chains require suppliers that can challenge requirements that seem unreasonable and customers that are receptive to the concerns and ideas expressed by their suppliers. By working closely together, companies can frequently eliminate or modify poorly chosen performance requirements and thereby significantly reduce cost.

9.3 THE IMPACT OF COMMUNICATION ON SUPPLIER INNOVATION

The case studies reported earlier indicate that close and open communication plays a central role in fostering innovation across supplier networks. Good communication can be described along a number of dimensions. In the early stages of a new program, communication between customers and suppliers helps both parties to arrive at product designs that perform well and that can be produced affordably. This was confirmed through discussions with many of the companies that participated in this study. In a few cases, it was noted that parts could have been designed better had suppliers been more closely involved early in the design stages of the F-22 program. As a whole, however, emphasis on inter-firm communication in design and development seems to have significantly increased in recent years. This is especially important in the defense aerospace context because the greatest potential for opportunities for product innovation lie in initial design phase of the program. Once a design becomes fixed, further improvements are often constrained by re-qualification requirements, desire to maintain commonality, and a variety of other factors. Due to the longevity of most fighter aircraft platforms, the benefits of innovation, as well as the costs of poor design decisions, will remain with a program for many years.

Communication has also been an important enabler of innovation during the continuing EMD and early production phases of the F-22 program. As mentioned above, achieving the performance requirements associated with many of the F-22's avionics components has been a major challenge for many suppliers. Intense collaboration between customers and suppliers has been essential to ongoing efforts to achieve technical objectives and reduce costs to feasible levels. A number of subtier suppliers reported that frequent visits to their facilities by personnel from customer companies have been very helpful in solving technical problems and improving processes. In several cases, suppliers' engineers reported speaking almost daily with their counterparts at customer organizations. Communication frequency tended to vary with the technical complexity and difficulty encountered in meeting a particular product's requirements. Good communication has also been critical in discussing tradeoffs in various performance attributes and the effects on cost. Innovation can often mean realizing where one can accept lower performance in one attribute of the supplier's product in exchange for higher performance in another.

9.3.1 Ensuring Communication Does Not Become Counterproductive

Communication can actually hamper innovation across suppliers if it becomes too disorganized. A potential danger of greater communication between individuals at collaborating firms is that it may cause confusion rather than producing a synergy of ideas. As more information is exchanged among an increasing number of people, it becomes harder to keep everyone involved apprised of the latest developments and most recent decisions. Discrepancies may arise between members of different groups about agreed upon solutions to problems. For example, two engineers at a supplier may each talk to different counterparts at the same customer, and later find out that they have decided on conflicting plans of action. Managing communication flow can be particularly difficult for major suppliers or subcontractors that have to interact with many of their own suppliers as well as with many representatives of their customer company. The contracts manager for one such company noted that keeping track of frequent design changes and their impact on contract terms (such as price and delivery time) was an extremely difficult and frustrating task.

Companies need to establish effective systems for clearly communicating changes to members of their own organizations as well as to their suppliers and customers. One smaller supplier found the best method for structuring communication was to require that it all be routed through the program manager. Rather than the supplier's engineers directly calling the customer, they were required to first discuss their ideas with the program manager. He then shared these ideas, as appropriate, with contacts at the customer organization. In some cases, the program manager would first consult with other engineers within his company to ensure that proposed solutions would not interfere with other aspects of production or product performance. While this sometimes slowed down the communication process, it paid off by making the process more productive. It helped to avoid confusion resulting from multiple communication channels, and often saved time through early elimination of bad or previously attempted ideas.

9.3.2 Maintaining Awareness of New Developments, Standards, and DMS

Awareness of new technological developments, industry trends, and evolving standards was also found to be an important enabler of innovation. This awareness depends on open and effective communication across the supply chain. Customers must understand how the capabilities of their suppliers are changing and the opportunities and threats this represents to their own product. Likewise, suppliers benefit from knowing the long-term needs of their customers, which helps them to tailor their development efforts. For major defense aerospace companies, a key to minimizing the negative impact of DMS lies in recognizing and anticipating potential DMS sources. As discussed in earlier, a decision by third or fourth tier suppliers to discontinue or alter their production processes often disrupts the entire supply chain. Because subtier suppliers often have more visibility into potential DMS issues before they arise, they play an important role in communicating these dangers in advance to the final producers. In addition, they can provide insights into how decisions upstream might affect future availability of critical components.

Communication with suppliers regarding industry trends and standards helps customers to choose product architectures and set design requirements that will be viable well into the future. This is particularly important in a fast clockspeed technology environment like avionics. It also helps customers to know when upgrades and architectural modifications are appropriate. For example, one major problem experienced by Lockheed Martin on the F-22 has been obsolescence in interfaces in the avionics system. The interface design was chosen in the 1980's and is unique to the F-22 platform. Had designers been able to better anticipate the direction of interface standards, they may have chosen a more robust and adaptive design that would have ended up being more compatible with current technology. Knowledge of emerging technology in the supplier base is also important. It enables customer companies to incorporate the latest innovations by suppliers into new designs and capitalize on advances that enable greater performance and improved manufacturing processes. For example, developments in MMIC chip technology (such as the shift from MESFET to PHEMT) or advances in wafer fabrication equipment could significantly improve the reliability and decrease the production costs associated with the major avionics subsystems provided by BAE SYSTEMS and ATC. Equally important, customers can strengthen suppliers' capabilities by proactively transferring technology and know-how to them. This can then spur further innovation by suppliers, creating a virtuous cycle of continuous improvement that strengthens the entire extended enterprise.

9.3.3 The Challenge of "Hub-and-Spoke" Communication Flow

Another finding that emerged from the case studies was that communication flow between customers and suppliers on the F-22 program often followed a hub-and-spoke pattern. In some cases this has prevented or slowed down the exchange of information, especially across lower tier suppliers. Due to the complexity and tight design margins of the major avionics subsystems, integration of the many parts comprising them is a major challenge. Slight modifications in supplier A's part might disrupt the functioning of supplier B's part. However, the systems integrator has a difficult time assessing where the real fault lies. Supplier A may have believed it was simply improving its product, unaware of how the change would hinder integration with supplier B's product. Had Supplier A communicated with supplier B beforehand, it may have realized the potential problem its modification would pose. Unfortunately, communication channels exist primarily between the customer and its suppliers, and not between or across suppliers. Supplier A discusses ideas with the customer, which then consults with other suppliers concerning questions about potential conflicts with their designs. All communication is routed through the customer hub. This is shown in Figure 9.2 below. Each S represents a supplier and the arrows denote the flow of communication that would have to occur if supplier #1 wanted to make a change to its product that could affect the functionality of supplier #3's product. The process might be more efficient if suppliers could identify other suppliers which might be affected and directly discuss their proposals with them. Going through the customer may introduce errors in transmission and considerably delay the process. These difficulties that are introduced through the use of a hub-and-spoke communication system tend to discourage suppliers from pursing new ideas, particularly when they face schedule-driven time pressures. On the other hand, there is perhaps also the danger described earlier that communication could create confusion if too many parties are involved and its flow becomes disorganized. Therefore, a balance must be reached between encouraging discussion across suppliers while ensuring that the customer company is involved in decision-making processes and aware of any changes that occur.

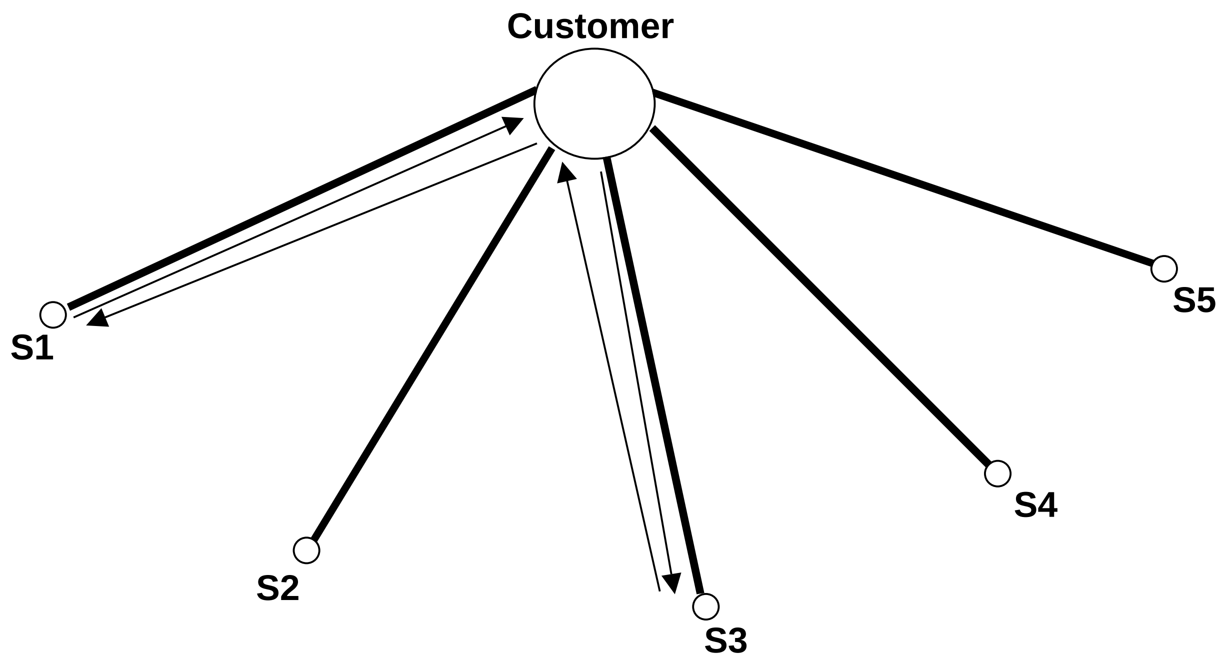

Figure 9.2 – "Hub-and-Spoke" Model of Communication Flow

One reason for the aforementioned pattern of communication flow is that customers desire to limit access to proprietary information and keep designs secret. As a result, most suppliers have little idea about how their product integrates into the larger system. Due to their limited visibility of the project, they have no choice but to communicate through the customer. This can restrict the ability of suppliers to optimize their designs and to help customers solve problems encountered during integration. The supplier is simply asked to produce a product according to an agreed upon set of specifications. Changes may only occur when specifically requested by the customer. This clearly inhibits supplier innovation. On the other hand, secrecy may require such arrangements in some circumstances within the defense aerospace industry. Nevertheless, companies should carefully evaluate the level of secrecy that is really necessary. It is important to recognize the constraints secrecy can place on innovation and determine whether the tradeoff makes sense.

9.4 METHODS OF FOSTERING INNOVATION THROUGH COMMUNICATION

Given the clear role it plays in fostering innovation, how can companies increase communication across their supplier networks? This section discusses a number of potentially useful approaches to this problem, many of which companies have already successfully undertaken.

9.4.1 Preferred Suppliers

One decision made by the two major subcontractors in this study in recent years has been to trim their supply chains. They have significantly reduced the number of suppliers involved in new programs and identified a short list of preferred suppliers with which they have established closer, more tightly-knit, relationships. This has helped to focus their resources and maintain more frequent communication with suppliers possessing critical capabilities. ATC has provided their own designers with a web-based list of these preferred suppliers, including links to their points of contact, technical capabilities, and involvement in past programs, thereby enabling them to quickly locate supplier resources. As a result, it is more likely that engineers at the customer and supplier companies will begin talking to each other from the very beginning of a new program.

9.4.2 Cost Review Sessions

Subcontractors have also initiated closer communication by holding cost review sessions with their own respective suppliers. These sessions were initially motivated by the F-22 program's emphasis on cost reduction. However, their benefits extend beyond simply cutting cost. Such reviews are helpful in fostering innovation. The customer and supplier jointly review the product's requirements (both performance and testing), manufacturing methods, and cost structure. They are often able to identify areas of waste, opportunities for product improvement, requirements that can be eliminated, and more efficient methods of production. In addition, cost review sessions help to increase familiarity between the companies, enhance the customer's understanding of the supplier's capabilities, and clarify the customer's needs to the supplier.

9.4.3 Gatekeepers

While most companies did not employ people specifically as "technological gatekeepers", subcontractors had engineering groups devoted to scanning the technology landscape. These groups provide useful input to designers about new developments, particularly in the microelectronics industry. However, regularly surveying the supplier base for valuable new technological advances was not seen as a major task. Because so few suppliers of critical defense electronics exist, most designers at the customer company are knowledgeable about who they are and their capabilities. Although frequent advances do occur in the much larger commercial industry, most of these are reportedly not directly applicable to defense products. In fact, it was argued that the defense sector continues to drive much of the core technological innovation in microelectronics. Unfortunately, it was not possible to investigate in greater depth the extent to which emerging commercial technologies may be adapted to defense purposes, and whether more should be done to search out these opportunities.

9.4.4 Supply Chain Mapping

As discussed previously, companies in the study found supply chain mapping exercises to be very helpful in improving communication and identifying areas most in need of improvement. They found it helped them to visualize the extensive network of companies that must coordinate activities and improved understanding of critical drivers of cost and performance.

9.4.5 Collocation of Engineers

Collocation of engineers from different companies during the design and development process, as an institutionalized practice, rarely occurred in the F-22 program. Although it cannot be definitively concluded that this would have fostered greater innovation, it appears it might hold the potential for doing so. Discussions with the F-22 program manager at one subcontractor revealed that collocation of engineers from different functional groups was a strategy that had been employed with great success at his company. It encouraged valuable face-to-face dialogue among engineers, something that would not have occurred through e-mail or telephone calls from one end of the company to the other. In addition, collocation of technical personnel from customer companies and their suppliers is a strategy Japanese manufacturers have followed for decades (Womack 1991). If intra-company collocation has proven successful for defense subcontractors, it seems inter-company collocation could likewise be beneficial and should be considered by defense aerospace manufacturers.

9.4.6 Information Technology

An enhanced information technology infrastructure linking customers and suppliers also holds the promise of fostering greater innovation. One of the biggest problems faced by major programs is coordinating the activities of numerous suppliers to produce a highly-integrated, complex system. Although e-mail and the Internet have done much to speed up communication in recent years, it seems far more could be done to organize the flow of information and increase visibility of activities across the supplier network. A large IT system linking a program's participants could potentially provide an important solution.

Such an IT system might include updated information describing the program's progress, the suppliers involved, points of contact at various organizations, recent design changes, and critical decisions that have been made. Major defense contractors would host the system, with lower-tier suppliers using smaller software modules to access information pertinent specifically for them. The system could offer tools such as a "virtual integrator", which would accept component specifications as inputs and predict whether various supplier components will fit together and perform as expected. It would help companies to quickly determine how small design modifications to their product would impact the larger system. Such an IT infrastructure would also help to prevent confusion about changes made by different groups within an organization, by providing instant access to the most recent documents. Many other benefits can be envisioned as well. Although the infrastructure would be costly to develop, it could prove a valuable tool for building an innovative supplier network. Along similar lines, Lockheed Martin has already developed a successful inter-firm software development network. The network links major subcontractors and helps to ensure proper integration of software code across avionics subsystems.

9.5 FOSTERING INNOVATION THROUGH SHARED INVESTMENTS

Defense contractors have invested heavily in many of their suppliers in the form of technical assistance and time. In many cases, Lockheed Martin, BAE SYSTEMS, and ATC have devoted considerable engineering resources to developing supplier capabilities and helping them to improve their products. These efforts have been very important in achieving the ambitious performance goals of the F-22 program and in reducing supplier costs. They have led to innovations in products and processes and improved communication with suppliers. However, it has been possible to document only a few cases of companies sharing in financial investments with suppliers, supporting actions by suppliers such as purchasing capital equipment, redesigning a product to increase its manufacturability, or engaging in research and development. Yet innovative ideas often require significant up-front expenditures, which suppliers may be unable to afford or unwilling to make alone, in order to develop the ideas and capitalize on the benefits.

9.5.1 Problem of Allocation of Investment Benefits

There are a number of reasons for the fact that sharing in investment costs between the customer companies and their suppliers has not occurred in the F-22 program, and perhaps more generally in the defense aerospace industry as a whole. One reason is that capital investments often provide benefits that are difficult to specifically allocate to individual customers. For example, a new piece of manufacturing equipment may enable a supplier to produce its F-22-specific component for less, but it will also allow the supplier to produce non-F-22 products for many other customers more cheaply as well. The supplier's F-22-related customer would generally not help to fund such an investment because only a small portion of the benefits accrue to that customer company and it would likely be difficult to assign a value to these benefits. In the case of R&D investments, it was found that suppliers often prefer not to receive funding from their customers. Instead, they typically seem to prefer to fund research and development themselves in order to ensure that they retain full rights to the resultant intellectual property.

9.5.2 Capital Constraints

Smaller suppliers are often constrained by limited access to capital. They may not have the financial resources or the flexibility to make large up-front investment payments when already strapped for operating cash. A financially strong customer company can help by providing the necessary funding to support the investment in exchange for a share of the payoffs later. Of course, customer companies also have financial limitations. They can assume only so much debt and plow only so much of their earnings into further investments, even if the investments have high payoffs. Therefore, customers cannot afford to act as bankers for every supplier that needs help. They must be selective about which projects they support.

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9.5.3 Impact of Program Uncertainty

Uncertainty about the future of the F-22 program has discouraged shared investments as well. Since companies do not know for sure how long the program will be supported by the government and what volume of planes will eventually be purchased, they often shy away from investments. Many of potential investments are extremely expensive and would only pay for themselves if the program remained healthy well into the future. Furthermore, customer companies are sometimes uncertain about the ability of particular suppliers to meet future demands. Investing in a supplier underscores long-term commitment. However, this may reduce the supplier's motivation to improve its performance to avoid losing the contract to a competitor. In some cases, uncertainty about the future of a design also deters investment. In a fast clockspeed environment like avionics, there is constant danger that changes in technology will render portions of a design obsolete and will necessitate major design modifications. These changes in the product could quickly negate the value of manufacturing equipment that was specific to the old design. For example, one supplier purchased expensive new test equipment in order to meet stringent test requirements of its customer. Shortly thereafter, an improvement to the design made the particular tests performed by that equipment no longer necessary.

9.5.4 The Effect of Contract Structure on Investment Incentives

Some suppliers also reported a reluctance to make investments with long payoff periods due to the F-22's yearly, fixed-price contract structure. If an investment enables a supplier to reduce costs, the customer will often demand a lower price when negotiating the new contract the following year. However, if the supplier cannot continue to capture the cost savings from its investment over several years, it may never be fully compensated for its cost. Only when the payoff period is less than a year and the price is fixed will the supplier be assured of receiving additional profits by reducing costs through good investments. Unfortunately, this lends a short-term focus to suppliers' investment activities.

9.5.5 Need for External Funding

Discussions with suppliers indicated that many investment opportunities exist throughout the supply chain. In fact, the emphasis on cost reduction, coupled with the many cost review sessions, supplier conferences, and other activities initiated by the Lockheed Martin and major subcontractors, have stimulated a host of innovative improvement ideas. For many of the reasons described above, however, companies have foregone many of them. In part in recognition of this, the government has taken steps to encourage investments through its funding of Producibility Improvement Projects (PIP) under the War on Cost Initiative. This external funding has helped to overcome investment barriers, and can help create considerable cost savings for the program over the long term. However, discussions with suppliers indicate that only a small fraction of improvement ideas have actually received support. Some suppliers have complained that after devoting extensive efforts to identifying opportunities for cost savings, customers have not followed through with the resources required to pursue them. According to Lockheed Martin, which evaluates the proposals for cost savings submitted by suppliers and allocates the limited government funding, projects must offer more than seventeen times return on investment to receive consideration. Many good proposals with slightly lower returns have been put aside, despite their promise for further reducing the program's overall cost and perhaps benefiting future programs like the JSF. It appears the government would profit from enlarging its funding pool to support more investment projects, which in the long run would produce considerably more cost savings. Otherwise, a large number of these investments will not be made, as suppliers possess neither sufficient capital resources nor incentives to do so on their own.

9.5.6 When should companies consider sharing in supplier investments?

The concept of sharing in the cost of investments with suppliers is a relatively new phenomenon, particularly in an industry with a long history of arms-length relationships. As aerospace supply chains have become more partnership-based, managers have increasingly faced the decision of whether to collaborate financially with suppliers. Several good guidelines for making such a decision have emerged from discussions with companies in this study. First, the customer company should have a reasonable ability to observe the level of cost savings actually realized by the supplier as a result of a shared investment. This is necessary to ensure that the supplier passes on a share of the cost savings commensurate with the customer's investment. This criterion is often met in defense aerospace contracting, where suppliers frequently open their books to customers. Secondly, the expected net present value of the future benefits from an investment project, when discounted by the risk-adjusted cost of capital, should outweigh the costs. This can be stated as

$$I_0 < B_0 + \frac{B_1}{(1+R_c)} + \frac{B_2}{(1+R_c)^2} + \frac{B_3}{(1+R_c)^3} + \cdots + \frac{B_n}{(1+R_c)^n}$$

where I_0 is the initial investment expense, B_i represents the expected value of benefits derived form the investment in year i, and R_c is the cost of capital, taking into account the riskiness of the project. If the customer had unlimited access to capital, it would want to support any project meeting the two guidelines above. Of course, in cases where a program's future is highly uncertain, B_i ***for i*** > 2 might be evaluated at zero, meaning that only investments with short payback periods would meet the criterion.

In reality, the customer faces some limit on available capital based on the financial structure of his company. Even if offered an infinite number of positive net present value investment opportunities, it is restricted by the debt and equity it can raise to fund them. Therefore, it should prioritize projects according to their risk and expected returns. In some cases, it may make sense for the customer to fund a supplier's project, which has higher returns, rather than fund a project within its own company.

Finally, the customer should consider how investments proposed by a supplier fit into the supplier's overall business structure. Would the investment be specific to the relationship, or would the supplier derive benefits from across a wide range of products that it sells to other customers as well? In the latter case, the supplier should probably be expected to make the investment independently, since it is central to its broader business operations. On the other hand, if the investment primarily benefits one customer, or a large portion of the supplier's business is associated with one customer, it may be wise for the customer to share the cost. The customer should also have an understanding of the supplier's needs in determining the appropriateness of financial support. If the supplier is a large company with sufficient access to capital, making shared investments makes less sense than if the supplier is a small firm faced with severe financial limitations.

9.6 LEAN TRAINING AS ENABLER OF SUPPLIER INNOVATION

Lockheed Martin has made an effort to train most of its major suppliers in the basic principles of lean manufacturing. Major subcontractors like ATC and BAE SYSTEMS have also established ongoing lean initiatives at their companies. However, major subcontractors have only recently begun training their suppliers. In some cases, training has been unnecessary because suppliers have already adopted lean practices on their own. In other cases, suppliers are so small or their share of total weapons system costs so small that lean training may not exhibit a clear business case Nevertheless, it appears that some opportunities continue to exist to help suppliers become more innovative in the way they think about and manage their processes. Companies, including both major defense contractors and lower tier suppliers, which have been taught and endeavored to apply lean principles, have reported significant improvements in their manufacturing operations, supplier relationships, product development processes, and other business aspects. The Air Force and DoD can also take steps to be “leaner” in their procurement practices and to help spur supplier innovation, as will be discussed in later sections of this chapter.

Lean training of suppliers helps to diffuse process innovations developed through the customer company’s experience. Although the case studies did not uncover specific examples of innovations stemming directly from the adoption of lean practices that could be closely studied, a number of those interviewed felt that lean training had been important in helping to develop an eye for waste among their company’s employees. Ability to recognize problems that exist is essential to developing innovative solutions for overcoming them. Supplier H provided one example of a smaller supplier that reported greatly benefited from the lean training offered by its customer. On the other hand, several subtier suppliers were not confident that lean training by their customers would make a significant difference in their operations. They claimed to have already taken steps to solve what they perceived to be the major problems and bottlenecks in their companies and did not anticipate that additional help from their customer would result in significant improvements. While this may be true in some cases, it could also represent an initial skepticism of new ideas. At the least, the customer might benefit by observing innovations by the supplier that may be applicable to its own company.

In order for lean training to truly foster innovation among suppliers, customer companies should avoid teaching it as simply a fixed set of rules to follow. Such an approach leaves no room for innovation and may even be counterproductive. The defense aerospace industry is unique, and even within the industry, distinct characteristics differentiate the many companies. Therefore, a "one-size-fits-all" approach to "lean" should be avoided. What works well for one company may be wrong for another. Even within companies, there may be practices that are generally good, yet inappropriate in certain circumstances. Customers should teach suppliers lean ***concepts***, and give them latitude in determining how these concepts apply to their particular business situations. It is important that a suppliers' employees firmly grasp the underlying principles and that they can develop solutions most suitable to the specific conditions encountered in their company. It is particularly helpful when "lean champions" emerge within companies. This term typically describes a small number of key employees who have both been well trained in lean principles and clearly understand the company's operations.

9.7 CONTRACT STRUCTURE INCENTIVES AND BARRIERS

Through discussions with companies, it has been determined that the design or structure of contracts has a strong effect on propensity of suppliers to innovate. Most F-22 contracts in the early production phases (i.e., PRTV, Lot 1, Lot 2 to date) have been firm fixed price. This structure is expected to continue through full-scale production, with successive lots being negotiated on a roughly yearly basis. The choice of suppliers is also expected to remain fairly constant, although for some items customer companies may compete upcoming lots and select alternative low-price sources to replace previous ones. Unfortunately, it has been found that the structure of F-22 contracts often provide more disincentives than incentives for suppliers to innovate.

9.7.1 Target Costing and Profit Sharing

Traditional lean concepts of incentivizing supplier performance through target costing and profit sharing have rarely occurred on the F-22 program, and generally do not seem to be in evidence in the defense aerospace industry. This stems partly from the nature of the industry itself. The premise of target costing and profit sharing is that suppliers should be rewarded for reducing prices below an expected level. However, this implies that the customer company has a good estimate of what the price level should be. Many aerospace products are unique and incorporate cutting-edge technology. Customers cannot easily estimate costs in advance, nor can they always distinguish truly innovative performance from standard practices and easily put a value on it. A customer company has a particularly difficult time assessing whether a supplier's initial price quote is reasonable when no competition exists to provide a point of comparison. If the supplier has no incentive to bid low to win a contract, then later rewarding it for reducing costs below an already high level does not make sense. On the other hand, failure to reward suppliers for exceptional performance sometimes results from a short-sighted focus on cost within the defense aerospace community. Acquisition personnel, for instance, can become so focused on preventing excessive profit-taking by the contractors that they eliminate rewards necessary to motivate supplier improvements that will reduce future costs. Although acquisition personnel officially deal directly only with the prime contractors, many of the contractual terms and agreements are in fact flowed down the entire supplier chain and impact relationships at all tiers.

9.7.2 Long-term Price Commitments

In this study, creative contractual arrangements for incentivizing supplier innovation were not observed. However, several companies felt that one effective means of incentivizing greater innovation would be to offer suppliers long-term price commitments in their contracts. Due to program uncertainty and contracting regulations this is not currently done. Long-term price commitments imply that the customer would negotiate a fixed price for a product with a supplier and agree to continue purchasing items at this price for several years. The supplier could keep any additional profits gained by reducing costs below this price over the stated contract period. In exchange, the supplier would agree to reveal its cost structure upon renegotiation. Thus, the supplier would have an incentive to minimize costs, while the customer would benefit in future contract periods from lower prices as a result of the supplier's efforts. The defense aerospace community should give more attention to contractual approaches such as this one in order to tap the full creative potential of the supplier base.

9.7.3 Disadvantages of Annual Contracts

As mentioned above, the short-term nature of F-22 contracts can discourage innovation by deterring companies from making long-term investments. The yearly negotiations also consume considerable time, both at customer and supplier organizations. The continual focus on reaching contractual agreements for the next period can distract companies from their primary focus of manufacturing innovative products. This is particularly true at smaller suppliers, where employees wear several hats. Time at the negotiating table decreases time devoted to overseeing development and production. One of the clearest solutions for eliminating these problems, encouraging innovation, and reducing supplier costs, is multi-year contracting. Nearly everyone interviewed advocated more frequent use of this approach, although they acknowledged that some barriers (i.e. program uncertainty) exist to multi-year contracting.

One advantage of multi-year contracts would be that companies could procure material in larger quantities to receive volume discounts. In some cases, they could also reduce variation between shipments and the potential for DMS problems by purchasing critical items in advance. Companies might choose to manufacture products in larger, more economic, batch sizes to avoid lengthy set-up times associated with small orders. In addition, companies would be more prone to invest not only in their own operations but also in their relationships with suppliers. They would be more willing to commit to suppliers and help them develop key capabilities, which would have obvious benefits in terms of reliability, innovation, and cost. Furthermore, they would invest in the intellectual capital of their companies, hiring top-notch engineering talent and training workers to increase their skills. While the advantages of multi-year contracts are evident, however, implementation has been slow. Much of this can be blamed on the government's acquisition policies, constrained by Congressional oversight. Uncertainty about the level of funding that Congress will approve and how the funding will be allocated to various defense programs in upcoming years prevents acquisition personnel from making long-term guarantees to prime contractors. In turn, this uncertainty is embedded in contracts throughout the supply chain and becomes a costly barrier to innovation.

9.7.4 Commonality, Combined Orders

In addition to multi-year contracting, other opportunities for reducing costs and spurring innovation include increased use of commonality across platforms and combining orders across different divisions of large customer companies. Higher production volumes tend to improve economies of scale and increase the suppliers' experience with a given product, encouraging the development of more efficient methods of production and improved designs. For example, ATC has attempted to increase commonality in its backplanes across several programs. By working closely with its suppliers, it has been able to leverage innovations in the backplane design for one platform to upgrade designs for older platforms. Another suggestion arising from discussions with companies was the idea of combining production lines for major subcontractors and prime contractors at critical electronics suppliers. Currently the production lines for various customers are kept separate and, due to low volumes, these production lines remain active only for a small portion of the year. The "stop-go" operation that then result due to infrequent use of the production lines increases variability between setups and limits the experience and familiarity of workers who operate them. Combining the lines would have obvious advantages in terms of consistency and reliability. It would also allow the customer to consolidate the capital equipment for various customers and utilize it more efficiently. This idea warrants further exploration.

9.7.5 Other Potential Incentives

Another way to reward suppliers for innovation is through award fee contract arrangements. Award fee contracts provide suppliers the opportunity to earn a portion of an award fee pool established at the beginning of an evaluation period. The customer determines the portion won based on evaluation factors set out in advance in an award fee plan. In some cases, the size of the award also depends on subjective judgment by the customer company of the extent to which the supplier exceeded certain minimum requirements (Mandelbaum, et al. 2001). Lockheed Martin has incorporated award fee elements into the structure of contracts with some of its major subcontractors on the F-22 program. However, no evidence was found indicating the use of award fees in contracts with subtier suppliers. Incorporating such arrangements may provide another means of ensuring that incentives for innovation exist throughout the supply chain. It would allow a supplier to earn more profits as the part it provides would bring greater value to the customer's system.

Interestingly, it was found that customers can also reward suppliers through non-monetary methods. It may be difficult to put a financial value on certain aspects of a supplier's performance. However, customers that are in-touch with their supplier base typically recognize the impact that supplier innovations can have on the final product. By applauding exceptional performance through various forms of supplier recognition, such as certificates of merit and other awards, customers can encourage future innovative efforts by their suppliers. Suppliers value the publicity and honors they receive as means for attracting new business. These awards also foster goodwill and trust between the two parties.

9.7.6 Impact of Government Contracting Policies on Supplier Innovation

Supplier contracts largely reflect the structure of the Defense Department's contract with the prime. The incentives for innovation that customer companies build into their relationships with suppliers generally depend on the incentives the government customer has included in its agreements with the prime contractor. If improving a weapons system's performance or reducing its cost does not increase the prime contractor's profitability, then the prime will be unlikely to reward its suppliers for improvements in their products. Thus, the DoD plays an important role in creating an environment conducive to innovation through its contracting approaches. It must lead the way in adopting creative, new contractual incentives that reward innovation delivered by the prime contractor, and in turn make it a primary interest of every firm in the supply chain.

Unfortunately, the primary incentive for many F-22 suppliers to innovate is the perceived threat of the program's possible cancellation. They recognize that the failure to reduce costs below a certain threshold could jeopardize the program's future and the prospect of future sales. For companies with a major stake in the program, such as Lockheed Martin, BAE SYSTEMS, and ATC, this provides tremendous motivation for reducing costs. However, a significant portion of total cost lies with smaller suppliers for which the F-22 program represents only a fraction of their aggregate revenues. For many of these suppliers, improving their product or passing on cost savings to their customer will not generate higher profits (and may in fact reduce them). As a result, there is not a strong incentive for innovation across the supplier base where the fortunes of individual companies are not at all dependent on the F-22 program.

Because the government plans to purchase a fixed number of planes, F-22 suppliers effectively decrease their own revenues by reducing their costs. Since they do not typically receive higher profit margins in exchange, their profits decline as well. This tends to dampen enthusiasm for innovation. A better approach may have been to make production volume contingent from the outset on price, with the government offering suppliers the prospect of increased sales in exchange for reductions in the plane's price. As Rogerson (1994) points out, "constant upgrading of systems that are in production is a very important part of the overall innovative effort in defense procurement." If suppliers succeed in improving their products, they should be rewarded with more sales, and consequently, with more profit.

It was found that subtier suppliers that earn a large share of their revenues from defense contracts tend to perceive substantial incentives to innovate in order to maintain relationships with the prime or major subcontractors. Many of these suppliers see involvement in the F-22 program as a key to positioning themselves strategically for opportunities with the Joint Strike Fighter and other defense programs. They do not necessarily expect to earn significant returns from their work on the F-22, but view it as a requisite investment to win more profitable future defense business in the future. However, the number of such suppliers dependent on defense business has significantly decreased with industry consolidation over the past few years. Many subtier suppliers are now very commercially oriented and major defense contractors do not have the same leverage over them.

Much of the oversight and regulation the government imposes on the prime contractor is also flowed down to its suppliers and act as a barrier to innovation. Many individuals interviewed at Lockheed Martin felt that certain Federal Acquisition Regulation (FAR) clauses unnecessarily restricted their design and sourcing options. Often, to receive approval for subcontracts, the prime contractor must submit many pages of detailed information to verify compliance with a long list of various contract criteria (Ellenson 1993). In turn, suppliers may be forced to spend considerable time compiling data for their customers and preparing for visits by customer or government officials. These activities can disrupt production work and distract key personnel at supplier organizations from other important tasks. Most subtier suppliers felt that the regulation environment had improved considerably in recent years, although several noted that more could be done. They indicated that reductions in red tape and government oversight had enabled greater focus on their core activities and increased productivity.

9.8 Government Support for an Innovative Supply Base

Beyond contract structures, the government plays an important role in fostering innovation through its funding of research. A large portion of past, key technological breakthroughs applicable to military fighter aircraft have been the result of government-supported research. In a study of innovation in the defense aerospace industry over the past 50 years, researchers Mark Lorell and Hugh Levaux identified three factors crucial to technology advancement: experience of contractors, competition, and government support for research (1998). They argue that in the new defense environment of limited competition and long gaps between major programs, the government must take an active part in ensuring that the supplier base maintains critical capabilities and continues developing new ones. This could include greater emphasis on developing new prototypes and demonstrating new technology. Other authors have argued for more support for unconventional and novel system concepts, coupled with a less bureaucratic acquisition process (Birkler, et al., 2000).

The F-22 program provides examples in which government funding has been an important enabler of innovation. These include the USAF Mantech-sponsored project to improve the radar manifold. In addition, the learning that has occurred over the course of the F-22 program has been a major contributor to the success expected from the future Joint Strike Fighter. The ambitious performance requirements which suppliers were challenged to meet on the F-22 stimulated numerous (even if costly) technological innovations. As there are fewer major programs today, the DoD can help to prevent technological stagnation by ensuring that suppliers continue to have new targets for further technology development, even if in the form of smaller projects. This means anticipating the critical defense technology needs of the future and supporting research among promising suppliers to meet them. In some cases the military can expect to leverage advances in commercial technology to meet future performance requirements. However, for other areas the military’s needs are unique and it will continue to depend on specialized technology solutions to meet them.

As industry contraction has occurred over the past few years, major contractors have streamlined their operations and increased their focus on core competencies. One subtier supplier suggested that this has diminished technology transfer to suppliers. Those interviewed argued that major contractors have scaled-back the quantity and breadth of research they conduct, and lower tier suppliers lack the resources to do more on their own. As a result, major contractors are more reluctant to experiment with new ideas suggested by suppliers. For example, the supplier may ask for permission to substitute a new material into their product. The customer will tend to refuse since he no longer conducts research to determine the feasibility of using such materials. A shift by major contractors away from all research not directly related to their core activities would indicate even greater need for government support of research in order to encourage innovation and technology diffusion throughout the supply base. At the same time, federal funding sources must be easily accessible. The same subtier supplier mentioned above rarely applies for government funds that are currently available. The approval process reportedly takes too much time and requires extensive and difficult-to-generate data demonstrating the potential payoff expected from the project.

Rogerson (1994) provides an economic framework to demonstrate the need for government subsidization of supplier research and development. He points out that in the defense industry, prizes for innovation are not well correlated with, nor commensurate to, the quality of innovation. In commercial industries, firms with major innovations (e.g. a pharmaceutical company introducing a new drug) stand to earn very high profit margins on their breakthrough products. Even under well-constructed contractual incentive mechanisms, however, innovative firms will rarely be rewarded to the same extent in the defense context. In fact, defense firms have historically earned fairly constant profit margins, regardless of the value of their innovation. Therefore, they lack adequate incentives to invest in developing technologies critical to the DoD. Rogerson argues that subsidized research provides a means to compensate for the absence of large prizes for innovation.

A further key observation of Rogerson (1994) is that in the long-run DoD's profit policy essentially determines the level of innovative activity in the industry. As the DoD adjusts the "fair" profit level it accords to companies in production contracts, firms enter and exit the industry until net profits become zero. The only long-run effect of a more generous profit policy is to increase total rent-seeking expenditures across firms. The same would be true of major subcontractors in their relationships with subtier suppliers. Therefore, profit policy provides another knob by which the government or customer companies can adjust the degree of supplier innovation. This insight, coupled with the knowledge that innovation needs vary among different defense technology areas, suggests that pricing rules should vary depending on technology being acquired. As the DoD identifies its strategic technology areas of interest, offering higher profits to suppliers in these areas may be justified as a means of encouraging innovation.

9.9 THE VALUE OF COMPETITION

It was also observed that some degree of competition acts as an important driver of innovation among suppliers. F-22 customer companies do not typically switch suppliers from contract to contract. Nevertheless, most suppliers recognize that the failure to innovate and reduce costs may well result in replacement by competitors in the long run. In the absence of credible competitors, however, suppliers may often tend to behave far more opportunistically. Most companies reported that sole-source relationships with suppliers have frequently been very problematic. These relationships generally occur when a supplier is the only company with the technological know-how and capabilities to produce a given item and is not highly dependent on the customer for its revenues. Such suppliers tend to charge extremely high prices for their products and are often quite unresponsive to the customer. Companies should avoid these sourcing situations whenever possible.

One key to avoiding sole-source relationships is to choose designs that do not rely on unique technological solutions or specialized processes and components. It is often wise to opt for more standard designs that several suppliers are capable of producing rather than sophisticated designs that depend on the particular expertise of a single company. Obviously, this is challenging when demanding performance requirements push the limits of current technology. Tradeoffs must be carefully weighed. In some cases, small sacrifices in performance may be well worth long-term savings in cost and reliability. Identifying sourcing traps requires good communication between design and manufacturing engineers and purchasing personnel. It is important for companies to develop methods for enhancing coordination across these three groups. This includes increasing designers' awareness of potential sources and their performance histories. It may also involve educating manufacturing and purchasing personnel about the technical implications of various design options and the strategic importance of various suppliers' capabilities.

9.10 TAKING A DIFFERENTIATED APPROACH TO BUILDING SUPPLIER RELATIONSHIPS

It should be noted that in discussing the drivers and enablers of supplier innovation above, this thesis does not advocate a "one size fits all" approach to building supplier relationships. The effectiveness of various practices and strategies in fostering innovation will differ across suppliers and products that are procured. Moreover, firms have limited resources and must be careful to allocate them appropriately across their supplier networks in order to generate the greatest return on their relational investments. The potential for innovation is not uniform across all supplier and some relationships hold greater strategic importance to customers than others. Therefore, companies have acted wisely in seeking to streamline their supplier bases and in selecting "preferred" suppliers with which to work more closely, as described above. In fact, some have even further classified their "preferred" suppliers into categories based on the criticality of the items the suppliers design and manufacture. In addition, the preceding discussion regarding competition highlights the need for the customer to consider the market conditions facing suppliers in structuring its supplier relationships.

One important perspective from which customers should evaluate their approach to supplier relationships is dependence. Figure 9.3 shows supplier relationships roughly classified into four categories and suggests appropriate strategies for each type of relationship. It is assumed in this figure that a company has already conducted a thorough make-buy analysis and decided to procure an item from suppliers rather than make it. In deciding the extent to which they should invest in various suppliers to foster innovation, customer companies may find it helpful to ask themselves into which quadrant of the matrix suppliers fit. Dependency, for suppliers, will typically be defined by the share of total revenues and degree of strategic learning derived from the customer. For the customer, dependency will typically center around the essentiality of the supplier's products and capabilities to its own core business and the availability of alternative sources.

MAPPING DEPENDENCE TO SUPPLIER RELATIONSHIP APPROCH

Supplier dependence on customer →

Customer dependence on supplier ↓

Customer dependence on supplier / Supplier dependence on customer	Low	High
Low	-arms-length relationship -minimal investment	-supplier has good understanding of customer's product, goals, & needs -invest in supplier but avoid over-commitment, maintain a few additional sources
High	-DIFFICULT SOURCING SITUATION! -establish clear & calculable rewards for supplier performance & innovation -consider producing item in-house, developing other sources -standardize design to increase number of potential suppliers	-close partnership -shared investment, training -frequent communication -supplier has good understanding of customer's product, goals, & needs -good understanding of supplier's capabilities

Figure 9.3 –Dependency Matrix

When neither party is dependent on the other, traditional, arms-length relationships are usually optimal, as market forces dictate outcomes and transaction costs are minimized. As suppliers are more dependent on the customer, investing in a smaller number of close relationships by the customer becomes more desirable. Suppliers will respond to greater customer commitment by investing in noncontractual assets and pursuing innovation to maintain customer satisfaction and support. Closer relationships also increase familiarity with the partner's products and processes and support collaboration in design and manufacturing. Nevertheless, the customer should maintain one or two additional sourcing possibilities to ensure competition, flexibility, and access to other potential sources of innovation.

In cases of mutual dependence, other sources may not be available to the customer or maintaining multiple sources may be too expensive. However, the customer does not need to be overly concerned about supplier holdup due to the supplier's dependence on it. This provides a strong incentive for both parties to develop a close partnership based on intensive collaboration and sharing of information and resources. Lastly, the lower left hand quadrant of the matrix represents the most difficult sourcing situation for buyers. The supplier does not depend heavily on the customer but recognizes the customer's dependence on itself. Therefore, the opportunity to gain future contracts from the customer does not provide a strong incentive for the supplier to perform. Instead, the customer should try to construct contracts that reward the supplier for innovation but also pass on some of the benefits to the buyer. In addition, the customer should perform a careful cost-benefit analysis to ensure that it would not be both possible and advantageous to produce the item in-house or develop other sources. The buyer might also avoid the lower left box by redesigning the item with more standard (rather than unique or specialized) parts and functions in order to reduce dependence on one supplier.

One of the difficulties associated with the F-22 is that a significant number of supplier relationships lie in the lower left quadrant. The prime contractor, the major subcontractors, and to some extent even some of the subtier suppliers, all acknowledged their frustrations in dealing with sole-source suppliers. In these cases, it is very difficult to incentivize supplier innovation or negotiate reductions in price. On the other hand, many of the supplier relationships examined in this research would fall into the lower right quadrant. A number of these relationships featured a considerable degree of mutual dependency between the customer and supplier companies. It appeared that many of the companies have been willing to make sacrifices in order to remain involved in the F-22 program and position themselves for future business from their customers.

9.11 OTHER BARRIERS TO INNOVATION

Several other features of the F-22 program that have presented barriers to innovation should also be noted. These primarily relate to the administration of the program and its impact on supplier actions.

9.11.1 Concurrency in Design and Production

At the same time suppliers are delivering production versions of their F-22 components and systems they have been completing the final phases of EMD. In effect, they have entered the production phase while still trying to finalize the actual design. This concurrency in design and production has been problematic, as suppliers scramble to adjust their production processes to accommodate a continually evolving design. Numerous engineering change orders (ECOs) have been generated in the process. As a result, suppliers have struggled to achieve consistency in their operations. Engineers have consumed large amounts of time chasing change orders rather than improving the efficiency of manufacturing processes. In some cases, the changes have required renegotiation of contract terms at several levels of the supply chain. In other cases, suppliers have been forced to make costly adjustments to their design or manufacturing systems without reimbursement. Furthermore, the concurrency in design and production has made it difficult to estimate the costs of future lots because the costs of present ones have been distorted by frequent changes. It would have been better to establish a firm design baseline before beginning the production phase of the program. Concurrency should be avoided where possible on future programs.

9.11.2 Program Uncertainty

As touched on previously, the uncertainty about the program's future acts as a major disincentive to investments necessary to support innovation. It lends a short-term focus to activities at all supplier levels. When companies lack assurance that the program will continue for many years into the future, they do not devote resources to developing dependable suppliers. Instead, they engage in yearly, time-consuming searches for new sources wherever previous sources have failed to meet requirements. Nor do companies devote sufficient resources to training their current employees and hiring new, top-notch engineering talent. They cannot engage in multi-year contracts where appropriate and reap the benefits of larger order volumes. Unfortunately, this uncertainty that handicaps the program largely stems from the funding instability that often characterizes defense aerospace programs. Any steps that could be taken to reduce funding instability would greatly benefit the industry and increase the value the US government would receive from its defense expenditures.

9.12 APPLICABILITY OF LESSONS LEARNED FROM THE F-22

The F-22 has been perceived by some to be an aircraft that is over designed and over cost compared with previously developed fighter aircraft. This raises questions about the extent to which it is representative of other programs and the challenges they face. In fact, many of the F-22's lessons were learned early on and have been applied in varying degrees to more recent programs, such as the JSF. For example, JSF designers reportedly backed off on cutting-edge technology in various areas in favor of lower costs. They have also learned from the problems encountered with the F-22's integrated avionics architecture and have used more COTS components where possible. The production volumes are much higher and it is hoped that the JSF will not experience the same level of program uncertainty that has plagued the F-22. However, many similarities between these two programs (as well as to some degree other major programs such as the F-18) still exist. The sourcing environment and state of the defense industry will likely be much the same, and perhaps even more challenging, as the JSF goes into production in several years. Furthermore, the JSF shares many of F-

22's key technologies (e.g. both use Pratt & Whitney F119 engines and new active electronically steered radar array technology) (Fulghum, 2000). Similar to the F-22, some reports have predicted major troubles ahead for the JSF, suggesting that many of its underlying technologies have not been sufficiently proven (Wall, 2000). Moreover, the JSF is still in early stages of development and its requirements are far from fully defined, leaving open the possibility that major revisions could occur. Nor has the fundamental "time-constant" problem been resolved, in which technology evolves much faster than new aircraft can be developed. It seems that in studying challenges that may lie ahead for the defense aerospace industry and in outlining appropriate approaches to handling them, the F-22 indeed provides an important test case, as one of the largest and most technologically advanced programs in production today. It is hoped that many of the lessons learned and codified through this research will be helpful to the defense acquisition community, major aerospace contractors, and suppliers alike as they continue working together to design, develop, and produce weapons systems for America's defense.

10 CONCLUSIONS AND RECOMMENDATIONS

10.1 INTRODUCTION

This thesis has sought to provide insight into the drivers and enablers of innovation within supplier relationships. It has focused in particular on the defense aerospace supplier base and explored the characteristics of supplier relationships within this industry context. The central goal of the thesis has been to suggest incentives, practices, and tools that aerospace companies can employ to foster innovation across their supplier networks. A parallel objective has been to identify barriers to greater innovation and recommend ways to overcome them. This chapter provides a concise set of conclusions that have emerged from this research, based on the analysis and discussion found in the preceding chapters. The reader should refer back to these earlier chapters for more in-depth explanations of the key issues and findings summarized below.

10.2 CHARACTERISTICS OF THE INNOVATION OBSERVED

The previously reported case studies have evidenced a high degree of “specified” innovation across the F-22 program. Suppliers tended to have a narrow scope within which to pursue innovation due to very tight design margins and highly specified performance requirements that were flowed down from customers. In many cases, the performance required of suppliers’ products was so ambitious and demanding that very few design options were left open to them for achieving the requirements. The complex and highly integrated nature of the F-22 avionics system has tended to restrict flexibility and limit the latitude for innovation at lower tiers of the supply chain. The complexity of the integration task and the interdependence of the suppliers involved underscore the importance of understanding and coordinating activities across the extended supply chain. Customer companies should be aware of how design decisions and contract structures impact not only immediate suppliers but also those several tiers below them. They should also be cognizant of potential threats to the design stability, quality, and affordability of their products that may lie deeper within the supply chain.

The greatest potential for innovation lies in the initial design phase of a program. Once designs have been fixed, strict requalification requirements found in the defense environment present a major barrier to subsequent innovation. Therefore, early involvement of suppliers in design and development is essential to fostering innovation and achieving affordability of weapons systems. Nevertheless, significant opportunities to benefit from innovation also exist in later stages of major defense programs. These include technology refreshes, process improvements, and the streamlining or elimination of performance and testing requirements. Performance characteristics and testing procedures, in particular, tend to be over-prescribed in the initial stages of new programs due to uncertainty about performance and integration. Testing requirements often drive a large share of avionics production costs. By reexamining performance and testing requirements, customer companies and suppliers have been able to eliminate many requirements that were unnecessary and identify more efficient methods of meeting others. By working more closely together, they have also been able to generate a large number of valuable product and process improvement ideas.

10.3 DIFFERENTIATED APPROACHES TO SUPPLIER RELATIONSHIPS

In designing a supply chain strategy that will foster innovation, companies should differentiate their relationship approach based on characteristics of each supplier and the products they supply. In general, companies should devote greater resources and efforts to building relationships with suppliers in critical technology areas, where important innovations are most likely to occur, than with suppliers of standard or commodity items. In addition, the dependencies of the customer on the supplier and vice versa are important variables to consider. Chapter Nine provides a dependency matrix that is recommended for companies to use in evaluating the types of relationships most appropriate for different sourcing situations. A high level of support and collaboration between the customer and supplier generally makes the most sense when both parties are highly dependent on one another. Of course, other factors such as product architecture and rates of technological change should also be taken into account in designing supplier relationships. Highly integrated product architectures and fast clockspeed technologies typically call for greater collaboration between companies, particularly in the early design phases of a program.

Competition among suppliers serves as an important driver of innovation. Sole-source relationships tend to be very troublesome, and companies should typically avoid them when possible. Sole-source situations often reflect poor design decisions, which often stem from inadequate communication between design, manufacturing, and procurement personnel. Designer engineers should avoid designs that rely on highly specialized components or processes, which only one supplier is capable of providing.

10.4 COMMUNICATION

The case studies show that good two-way communication is key to fostering supplier innovation. It is essential to exchanging ideas, maintaining awareness of emerging technology trends, coordinating design changes, and integrating complex systems. One way for customer companies to achieve greater communication with their suppliers is by streamlining their supplier networks and selecting a limited number of "preferred" suppliers on which to focus their relationship-building efforts. Through holding periodic cost reviews and brainstorming sessions with top suppliers, customer companies have also come up with many innovative ideas. One of the challenges associated with greater communication is organizing it to ensure that it does not lead to greater confusion or information discrepancies. The development of a greater IT infrastructure connecting major contractors and suppliers could help to improve systems integration, provide up-to-date notification of changes, and increase visibility of the supplier network. This research also suggests that collocation of supplier and customer engineers in the design process as well as supply chain mapping exercises have the potential to foster innovation through enhanced communication.

Unfortunately, the “hub-and-spoke” nature of the communication flow between customer companies and suppliers in the defense aerospace environment can sometimes present a barrier to greater innovation. Another barrier is created by concern among customer companies and the military for secrecy. This often limits the supplier's ability to understand the customer's need and offer more innovative ways to meet those needs. Finally, the tendency of some companies to cut back on resources and staff in recent years (often in the name of "lean") has made it more difficult for suppliers to gain the attention of key personnel at the customer company in order to discuss ideas. This prompted one supplier to state, "There is more interest in collaboration than ever before, yet fewer resources for doing so." Companies should be careful that in their fervor to eliminate waste they do not adopt "anorexic lean" practices that obstruct innovation.

10.5 SHARED RISK AND INVESTMENTS

The case studies indicate that sharing of investment cost and risk with suppliers rarely occurs in the defense aerospace industry. However, a significant number of lower-tier suppliers are capital resource constrained and/or unwilling to bear "asset-specific" investment risk alone. Opportunities for companies to benefit from sharing in supplier investments exist, and companies should identify and take advantage of them when they arise. It is important for customer companies to be aware of conditions in which investment sharing makes sense. These can be summarized by the following "investment sharing" checklist, which is described in greater detail in Chapter Nine.

- Customer has the ability to observe and share in the savings realized by the customer
- Investment has a positive net present value and the rate of return is competitive with investment opportunities within the customer's own company
- Investment is relatively specific to the customer's relationship with the supplier and not an investment general to the supplier's core business, which the supplier should make itself
- Limited size and financial capacity of the supplier represent a credible need for customer support

Uncertainty about the future of a program poses a major barrier to innovation by limiting investment in new technologies. Suppliers avoid making internal investments with long payoff periods and refrain from training and hiring of top-notch technical talent. Moreover, major suppliers keep looking for new suppliers, and thereby incur large switching and transaction costs from year to year, rather than making long-term investments to develop supplier capabilities and create lasting partnerships.

Government funding for Producibility Improvement Programs (PIPs) under the War on Cost initiative represent a step in the right direction in supporting supplier investments that will benefit the entire F-22 program. It appears that the War on Cost Initiative has resulted in numerous innovative product and process improvement ideas. However, in the interviews conducted in connection with the case studies reported earlier, many suppliers expressed their frustration that few of the ideas they have put forward have actually been implemented. To a large extent, this can be attributed to limited funding availability, since the returns on investment in the proposed projects have been typically quite high. This finding alone underscores one essential fact: there are potentially numerous opportunities for supplier-based innovation, many of which now practically go for the begging, that could potentially make a significant contribution to greater affordability in weapon systems acquisition.

10.6 CONTRACTUAL INCENTIVES

Contract structure and associated incentives have a significant impact on suppliers' motivation and willingness to innovate. However, very few F-22 contracts have employed target costing, profit sharing arrangements, or other incentive mechanisms. For many suppliers, the only incentive for innovation is avoiding program cancellation. This provides strong motivation for some suppliers with a major stake in the program, but less so for many others. Furthermore, innovations that reduce suppliers' product costs tend to decrease their revenues and profits, thereby creating a disincentive for innovation.

The government's contracting approach with the prime contractor heavily influences the structure of contracts across the supplier network. It sets the tone for how supplier relationships are managed at lower tiers and determines the contractual terms and conditions that are flowed down the supply chain. Hence, the government has an important role to play in creating a contracting environment conducive to supplier innovation. The fixed-price, annually negotiated contracts used in the early production phase of the F-22 program have discouraged some suppliers from making long-term investments. This research suggests that the use of multi-year contracts and larger volume purchases would significantly reduce costs and incentivize greater innovation. Concurrency in design and production has made it difficult for suppliers to estimate yearly lot costs and has led to a continual stream of design changes that create process instability and schedule disturbances.

The government and companies should work to establish more creative incentive mechanisms that will reward suppliers for outstanding efforts. These might include the use of price commitment curves, under which the customer agrees to a fixed price for the supplier's product for several years in advance, after which time the price is renegotiated based on the customer's assessment of the supplier's new cost structure. Award-fee contracts offer another method of motivating supplier performance. Non-monetary rewards such as special recognition and awards can also foster supplier innovation, as well as increase goodwill and trust between companies.

10.7 SUPPLIER TRAINING AND DEVELOPMENT

Training suppliers in lean practices can be an effective means of spurring improvements in manufacturing processes. However, it is not always necessary since some suppliers are already "leaner" than their customers. Suppliers benefit from having "lean champions" – individuals who understand both lean principles and the industry and company context in which to apply them. Customer companies can also help to foster innovation by identifying new technology directions and sharing them with the supplier community. Companies should also work closely with key suppliers to seek opportunities for subsystem commonality across platforms and programs. In some cases, innovations by suppliers in newer designs can be leveraged and applied to older platforms or across programs.

10.8 GOVERNMENT'S ROLE IN DEVELOPING AN INNOVATIVE SUPPLIER BASE

A large portion of key technological breakthroughs in the past applicable to military fighter aircraft have been driven by government-supported research. The DoD can play a central role in spurring innovation by subsidizing research in critical defense technology areas. This can help to prevent an "innovation-gap" between programs in an era in which there are far fewer active programs than in the past and long time periods between new programs. Suppliers often lack adequate incentives to innovate on their own because the potential for rewards in the defense environment is too low. Some subtier suppliers reported that along with defense cutbacks over the past few years, scaled-back R&D by major contractors has resulted in less technology transfer to lower tier suppliers.

Some smaller, subtier suppliers face financial strains, which are often exacerbated by government and customer company contracting practices, including long payment terms. Agreement on a uniform, streamlined set of specifications for the industry would improve the ability of suppliers to incorporate new technologies in their designs. Suppliers reported that they rarely take advantage of opportunities to obtain government support for research because the application process is too complicated and lengthy. Perhaps by streamlining this process, the government could provide greater stimulus to suppliers to pursue innovative ideas. Uncertainty about the future of acquisition programs typically creates one of the biggest barriers to innovation across the supplier network, and indeed across many of the prime contractors as well. Acquisition reforms that provided defense companies with greater assurance of the longevity of programs would substantially bolster innovative efforts across the industry.

APPENDIX

RESEARCH QUESTIONAIRE
Major Subcontractors

Lean Aerospace Initiative Research – *Fostering Innovation across Supplier Networks*

Researcher: Aaron Kirtley
Advisor: Dr. Kirk Bozdogan

Research Question: What incentives, practices, and tools can aerospace companies employ to stimulate innovation across their supply base?

Definition of Innovation: *the generation and implementation of new ideas which improve any aspect of a product or process and ultimately result in improved performance and/or reduced cost to the customer*

Examples of innovation include:
- Identifying and employing a new material which reduces weight of a component
- Developing or investing in a new manufacturing process technology that reduces manufacturing cost and/or improves quality
- Identifying a design modification that reduces parts complexity or minimizes potential obsolescence problems

Interview Questions *(All comments are non-attributable)*: Please comment on experience gained from your involvement with the F-22 program. Some questions may not be applicable to all individuals.

Questions regarding your company's relationship with your major F-22 customer
Please describe the primary item your company produces for the F-22 avionics system. Where does it integrate into the larger avionics system, and with what other key subsystems does it interact?

What are the critical performance characteristics of the item and the pacing technologies driving them?

How would you characterize the level of cooperation and trust between your company and the customer. Has your relationship with the customer or your suppliers been different on the F-22 program than other programs?

How well does your customer understand your company's capabilities and constraints? How well do you understand your customer's needs? What mechanisms exist to educate one another and increase mutual understanding and how successful have they been?

Describe the contract structure in each stage of the program (e.g. length of contract, award/incentive fees and criteria, how prices were determined). What have been the advantages and disadvantages, particularly in terms of incentivizing innovation?

Have there been any key innovations in the design or production of this item which have significantly improved performance or reduced cost? If so, what were they and what were the sources?

What are your company's primary incentives to innovate to improve the item you supply or reduce its cost?

What do you see as barriers to innovation?

Questions regarding your company's relationship with its suppliers

Who are your company's major suppliers for this product and what do they produce? Have these suppliers changed over the life of the program? What percentage of your suppliers are somewhat to heavily dependent on your company for revenue?

How would you characterize the outcome of the design, development, and early stage production of the item you supply for the F-22? What have been the major problems and major successes of this product and program?

What types of involvement did suppliers have in design and development efforts? What forms of involvement were most conducive to eliciting innovative ideas and solutions?

How were suppliers chosen to become involved in different forms of collaboration? How were key partners and IPT members selected?

In what ways have your suppliers contributed to any innovations in the product or its production processes? How do you encourage suppliers to do this?

What do you see as your suppliers' primary incentives to innovate?

What factors inhibit greater innovation among your suppliers?

How was R&D work on the product conducted and partitioned? What was the total dollar value? What portion was done entirely by suppliers and what portion was achieved through joint R&D efforts?

What is the current level of R&D is being conducted to improve the product, processes, and core technologies? To what extent are your suppliers involved in these efforts?

Have intellectual property issues been a concern, and if so, how have they been handled? Has fear of intellectual property loss discouraged the pursuit of innovation or sharing of knowledge?

Describe the structure of contracts with your major suppliers. What have been the advantages and disadvantages of these structures?

Describe the nature of your relationships with your suppliers. What levels of trust and cooperation exists?

What types and frequency of communication exists between your company and suppliers? What forms has this communication taken (e.g. IPT teams, data exchange via IT, co-located engineers, routine meetings/teleconferences)? Which forms have had the greatest positive impacts?

How well do your suppliers understand your needs and requirements? How well do you understand the capabilities and limitations of your suppliers?

How frequently do suppliers make suggestions for ways to improve your product or processes?

Do your suppliers collaborate and exchange information and expertise among themselves? In what ways has this occurred or been encouraged? Has this contributed to innovative ideas?

Do you routinely scan your supplier network for technology trends and advances? If so, how is this done and how successful have such efforts been?

Does your company or its suppliers often tap external sources of scientific or technical knowledge, for example from universities, research laboratories, or other industries? Has this led to innovation in your product?

Have there been mechanisms for risk sharing or sharing of cost savings with suppliers? Have you supported suppliers through shared investments? If so, what have been the results?

Have you provided training assistance to your suppliers? If so, how would you characterize its success?

Have there been any significant redesigns of your product? What were the reasons and what did the redesign entail? How was it funded? What was the role of your suppliers?

RESEARCH QUESTIONAIRE
Subtier Suppliers

Lean Aerospace Initiative Research – *Fostering Innovation across Supplier Networks*

Researcher: Aaron Kirtley
Advisor: Dr. Kirk Bozdogan

Research Question: What incentives, practices, and tools can aerospace companies employ to stimulate innovation across their supply base?

Definition of Innovation: *the generation and implementation of new ideas which improve any aspect of a product or process and ultimately result in improved performance and/or reduced cost to the customer*

Examples of innovation include:
- Identifying and employing a new material which reduces weight of a component
- Investing in a new manufacturing process technology that reduces manufacturing cost and/or improves quality
- Identifying a design modification that reduces parts complexity or minimizes potential obsolescence problems

Please describe the primary item you produce for the F-22 avionics system. What is its function, where does it integrate into the larger avionics systems, and with what other key subsystems does it interact? Who is the primary customer?

What are the critical performance characteristics of the item and the pacing technologies driving them?

Was the item uniquely designed for the F-22? If so, who was responsible for the design work?

Describe the competitive environment for the item your company produces? Does the customer have alternative sourcing options? How committed is the customer to buying from your company?

How would you characterize the level of cooperation and trust between your company and the customer? Please describe the nature of your interactions from initial design and development through low-rate production. Has this relationship differed from past relationships with the same customer?

Describe the contract structure in each stage of the program. What have been the advantages and disadvantages of these structures?

What do you see as your company's incentives to innovate to improve the item's performance or reduce its cost?

Have there been any key innovations in the design or production of this item or in the way it integrates into the customer's larger subsystem? If so, what were they and what were the sources?

What do you see as barriers to innovation? (e.g. frequent requirements changes, paperwork required with defense contracting, disclosure of cost or other proprietary data, delays, etc.) Have any barriers been eliminated or reduced in recent years?

What is the approximate dollar value of the contract for this item? How important is this contract to your company? How important are future production contracts for this item compared to past development work? How does defense business fit into the larger business goals and competencies of your company?

How much flexibility was your company given in the item's design? Did the customer provide explicit design specifications or more general performance-based requirements? How well do you understand the larger subsystem into which the item is integrated and your customer's needs surrounding the product he produces?

Are there steps your customer could take to foster greater innovation among suppliers? If so, what are they? What current practices have helped to stimulate innovation?

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LIST OF ACRONYMS

ASIC – Application Specific Integrated Circuit

ATC – Aerospace Technologies Corporation

CAB – Corrective Action Board

CAD – Computer-Aided Design

CAS – Cost Accounting Standard

CIP – Central Integrated Processor

CNI – Communication, Navigation, and Identification

COTS – Commerical Off-the-Shelf

DDS – Direct Digital Synthesizer

DFAR – Defense Federal Acquisition Regulations

DMS – Diminishing Manufacturing Sources

DoD – Department of Defense

ECO – Engineering Change Order

EMD – Engineering and Manufacturing Development

EOQ – Economic Order Quantity

ERP – Enterprise Resource Planning

EW – Electronic Warfare

FAS – Federation of American Scientists

FPGA – Field Programmable Gate Array

GaAs – Gallium Arsenide

IEWS – Information and Electronic Warfare Systems

IPD – Integrated Product Development

IPT – Integrated Product Team

JIT – Just-in-Time

JSF – Joint Strike Fighter

LA – Logarithmic Amplifier

LAI – Lean Aerospace Initiative

MIT – Massachusetts Institute of Technology

MCM – Multi-Chip Module

MMC – Modular Mission Computer

MMIC – Microwave Monolithic Integrated Circuit

MRO – Maintenance, Repair, and Overhaul

MRP – Manufacturing Resource Planning

NCO – Numerically-controlled Oscillator

NPV – Net Present Value

NRE – Non-Recurring Investment

PCB – Printed Circuit Board

PIP – Producibility Improvement Project

PRTV – Production Readiness Test Vehicle

RAIU – Remote Antenna Interface Unit

RF – Radio Frequency

ROI – Return on Investment

SAW – Surface Acoustic Wave

SMS – Stores Management System

SOW – Statement of Work

SPC – Statistical Process Control

STE – Special Test Equipment

TQM – Total Quality Management

VFR – Value Focused Relations