



INSTITUTE FOR DEFENSE ANALYSES

**Integrated Product and Process
Development Case Study:
Development of the F/A-18E/F**

Beth Springsteen, Task Leader

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Preface

This document was prepared by the Institute for Defense Analyses (IDA) for the Office of the Deputy Director, Systems Engineering in the Directorate of Test, Systems Engineering and Evaluation under the Office of the Under Secretary of Defense for Acquisition and Technology. As specified in the task titled Acquisition Case Studies, an objective of the task was to provide lessons learned from a defense program using advanced acquisition and development methods, including the use of Integrated Product and Process Development (IPPD) and Integrated Product Teams (IPTs). This case study will be used by the sponsor to help train the DoD acquisition community on the use of these key concepts.

The case study is a companion document to an earlier IDA study, *The F/A-18 E/F: An Integrated Product Team (IPT) Case Study*. The first case study captured the lessons learned by the Navy acquisition office when implementing IPTs, whereas this second case study captures lessons learned from implementing IPPD as viewed from the perspective of the prime contractor McDonnell Douglas Corporation (MDC).

MDC personnel showed a sincere interest in the case study and were extremely generous with their time, providing access to key personnel from multiple disciplines. A special acknowledgement is due to Mr. Jim Young, Division Director, F/A-18 IPT Engineering. He made many of his staff available for interviews and met with us a second time in Patuxent River, Maryland. A special thanks is also due to Mr. Mike Biggs, Program Engineering, E/F Technical Integration, who answered many questions as we wrote the case study and provided us with follow-up material.

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Executive Summary

Overview

This case study documents how McDonnell Douglas Corporation (MDC) used an Integrated Product and Process Development (IPPD) management philosophy to design and produce the F/A-18E/F aircraft. The paper identifies key IPPD principles and provides examples of how they were implemented by MDC. It examines the management practices, organization structure, and integrated tools used to foster the program's success. For students of the acquisition process in the Department of Defense (DoD), a list of discussion items and sample answers is provided.

The F/A-18E/F program was selected as the subject of the case study due to its achievements. In prior years, cancellation of three of the Navy's tactical aircraft programs, the A-12, A-X, and the Navy Advanced Tactical Fighter, had rendered the F/A-18 the Navy's only active tactical aircraft program. As such, it had a crucial role in naval air planning. Successful transition of the F/A-18E/F to full production, with particular attention to schedule, cost, and risk, was therefore vitally important to the Navy. In 1991-1992, well before IPPD and Integrated Product Teams (IPTs) became DoD policy, the program's achievements were recognized by DoD's first Acquisition Excellence Award. Dr. Paul Kaminski, the Under Secretary of Defense for Acquisition and Technology, noted the program's use of IPTs and continuous sharing of information as key factors in the program's achievements.

The material for the case study evolved out of a two-day visit by a study team from the Institute for Defense Analyses (IDA) to the MDC's St. Louis facility in Missouri. It captures the practices and benefits of IPPD as reported by the contractor; they were not independently verified by the study team. This case study is a companion to an earlier IDA case study¹, written from the perspective of the Navy program office, that traces the use of IPTs within the government acquisition office. The objective of these case studies was to document lessons learned from DoD programs using advanced acquisition and development methods such as IPPD and IPT.

IPPD Implementation on F/A-18E/F Program

IPPD is a management technique that simultaneously integrates all essential acquisition activities through the use of multidisciplinary teams to optimize the design, manufacturing, and supportability processes. IPPD facilitates meeting cost, schedule, and performance objectives from product concept through production, including field support.

¹ Bailey, Elizabeth K. and Beth Springsteen. *The F/A-18 E/F: An Integrated Product Team (IPT) Case Study*. Alexandria, VA: Institute for Defense Analyses, April 9, 1998.

Several key concepts and principles inherent to IPPD were critical to the effective implementation on the F/A-18E/F program: customer focus, concurrent development of processes and products, multidisciplinary teamwork, proactive identification and management of risk, and integrated information environment.

Customer focus is used to identify and to satisfy the customer's needs better, faster, and cheaper by including the customer in decision making and on multidisciplinary teams. From the beginning of the F/A-18 program, strong customer focus, including frequent and open communications between MDC and the customer, enabled the E/F to be an affordable evolution from the C/D and not become a "gold-plated" program.

Concurrent development of products and processes helps ensure that the product design does not drive an unnecessarily costly, complicated, or unworkable supporting process when the product is produced and fielded. Processes are developed concurrently with the products they support. By tailoring the design of the E/F to take maximum advantage of the manufacturing process, the E/F has 42% fewer parts than the C/D even though it is 25% larger. Moreover, the F/A-18E/F program was able to reduce production costs, defects, and rework by creating production processes and hardware designs simultaneously and carefully analyzing the sources of variation in the process.

Multidisciplinary teams comprise members from technical, cost, manufacturing, and support organizations, including both customers and suppliers. These team members are empowered to make decisions for their respective organizations and to keep them informed of the product and process decisions. On the F/A-18E/F program, schedule, and technical parameters were allocated down to Level 5 of the Work Breakdown Structure (WBS), equipping teams to do their jobs. Moreover, team leaders were given the appropriate authority over product, process, and personnel to get the jobs done. Weekly reporting of metrics kept teams informed and accountable. Organizational structure mirrored product structure, enabling the team structure to evolve with the life cycle. Finally, skills of team leaders were critical to the success of teams.

A proactive approach for identifying and managing risk areas is also critical to the successful implementation of IPPD. MDC uses an organized, comprehensive, and iterative process for identifying and analyzing cost, technical, and schedule risks and instituting risk-handling options. Even though risk was minimized from the outset because the F/A-18E/F had evolved from the C/D program, risk was still an important concern. Proactive identification was accomplished through the overarching management philosophy of recognizing problems early on (through weekly reporting mechanisms) and asking for help. Once system requirements were allocated to teams, the teams then used a formal risk management process to identify risks, analyze them in terms of their likelihood and consequence, develop a risk management plan, and execute the plan to mitigate the risk. In this way, team leaders were able to identify tasks on the critical path and then work aggressively to execute them so as not to hold up the program.

An integrated information environment relates requirements, planning, resource allocation, execution, and program tracking over the product's life. It helps to ensure that teams have all available information, thereby enhancing team decision-making at all

levels. HornetWEB is MDC's secure intranet information system that provides MDC, the subcontractors, and the Navy program office real-time access to technical and business information. Integrated Management Information Control System is MDC's standard system for measuring and reporting progress at all levels. It enabled open communication and rigorous risk management to occur on the F/A-18 program by providing accurate, detailed progress measurements. Mod SDF is a collection of common database and analysis tools used to facilitate the exchange of engineering information across the product and technology teams.

Conclusions

IPPD enabled the F/A-18E/F program to meet its budget goals and be ahead of schedule with an air vehicle that was well below its specified weight. It is an improvement over the F/A-18C/D in nearly every measure, including reliability, maintainability, range, survivability, weapons carriage capability, mission flexibility, and future avionics expandability. MDC reports that implementation of IPPD principles was key to the program's success.

Chapter 1. Introduction

This case study examines the use of Integrated Product and Process Development (IPPD) in the design and production of the Navy's F/A-18E/F tactical aircraft. The events leading to and surrounding the F/A-18E/F program created an environment that placed a premium on open communication, affordability, adherence to schedule, and proactive risk management. This study examines how the F/A-18 program team at McDonnell Douglas Corporation (MDC) responded to these priorities using an IPPD management philosophy supported by an Integrated Product Teams (IPTs) organizational structure. It describes practices and benefits as reported by the contractor; the study team from the Institute for Defense Analyses (IDA) did not perform an independent assessment to verify these practices and benefits.

This paper is a companion to an earlier IDA case study, written from the perspective of the Navy program office, that traces the use of IPTs within the government acquisition office.² The purpose of both case studies was to document lessons learned from DoD programs using advanced acquisition and development methods such as IPPD and IPT.

In this case study, we focus on the application of various IPPD concepts and principles to the F/A-18E/F development process. The material for the case study evolved out of a two-day visit by the authors to the contractor's St. Louis facility in Missouri. A follow-up meeting was held in late August at the Navy's Patuxent River location in Maryland. It is noteworthy that their use of IPPD and of IPTs began in the 1991-1992 timeframe, well before these practices became DoD policy.³ The E/F model makes for an especially interesting case study because it represents an evolution from the earlier C/D model: thus we have a built-in point of comparison with the old way of building military aircraft.

We refer to the F/A-18 prime contractor as MDC, reflecting the name of the company at the time of most events described in the study. But in August of 1997, the Boeing Company purchased, which, in turn, became part of a Boeing Company business unit known as the Military Aircraft and Missiles Group. The F/A-18E/F is now the Boeing F/A-18E/F Super Hornet.

The outline of the case study contains 10 chapters. Chapter 2 presents the background of the F/A-18E/F program. Chapter 3 introduces five key IPPD principles: customer focus; concurrent development of products and processes; multidisciplinary teamwork; proactive identification and management of risk; and integrated information

² Bailey, Elizabeth K. and Beth Springsteen. *The F/A-18E/F: An Integrated Product Team (IPT) Case Study*. Alexandria, VA: Institute for Defense Analyses, April 9, 1998.

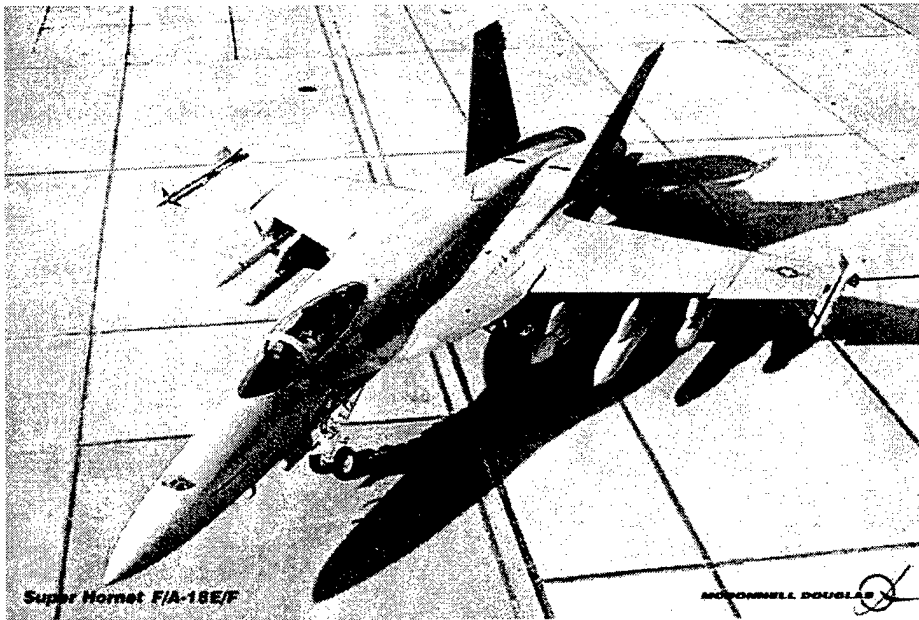
³ On May 10, 1995, the Secretary of Defense William J. Perry directed the "immediate implementation" of IPPD throughout the acquisition process to the maximum extent possible. Memorandum, Use of Integrated Product and Process Development and Integrated Product Teams in DoD Acquisition.

environment. Chapters 4 through 8 are rich with examples showing how the F/A-18E/F program applied each of these concepts and principles. Chapter 9 contains conclusions. Chapter 10 contains discussion items of interest to students of the DoD acquisition process. Appendix A contains example responses to each discussion item. A list of acronyms is provided at the end.

Chapter 2. F/A-18E/F Program Background

The F/A-18E/F is a twin-engine aircraft designed to fly from the Navy's aircraft carriers to perform both air-to-air and air-to-ground combat missions. The prime contractor is MDC. Northrop Grumman as the principle subcontractor builds the aft fuselage. General Electric is responsible for the engines. The E/F is an evolutionary design derived from the F/A-18C/D now in service. It is approximately 25% larger than its predecessor, has 35% more engine thrust and weighs 30% more at maximum gross takeoff weight.⁴ The E version carries a crew of one, while the F version is a two-seat configuration. Both versions can carry a wide variety of air-to-air and air-to-ground weapons on eight wing stations and on three fuselage locations.

The program entered engineering and manufacturing development in 1992 and passed Critical Design Review in 1994. Five E versions and two F versions are now conducting flight testing, and the program has entered low rate initial production.



Courtesy of the McDonnell Douglas Corporation.

Figure 1. F/A-18E/F Super Hornet

The F/A-18E/F is the Navy's only active tactical aircraft program, and will eventually perform most of the Service's air combat functions at least until the arrival of the multi-service Joint Strike Fighter, which is still more than ten years away. The program

⁴ See the U.S. Navy's Navy Fact File on the F/A-18 Hornet at <http://www.chinfo.navy.mil/navpalib/factfile/aircraft/air-fa18.html>.

reached this position by weathering turbulent years that included the cancellation of three of the Navy's tactical aircraft programs, the A-12, A-X, and NATF.

As the only remaining tactical aircraft program, the F/A-18E/F assumed a crucial role in naval air planning. Successful transition of the F/A-18E/F to full production was therefore vitally important to the Navy. Modernization was essential for both combat effectiveness and operational affordability because the existing fleet of C/Ds consisted of aging aircraft with limited options for capability improvement. However, in the wake of the A-12, A-X and NATF cancellations, Congress had mandated that the E/F could not exceed the cost of the C/D by more than 25%. Moreover, the Navy's reputation as an agency capable of effective aircraft procurement was at stake. In hearings on the not-yet-cancelled A-X, Senator John Glenn had said, "The Navy's ability to manage such a program is atrocious."⁵ Congressional sentiments like these helped focus the Navy's attention on schedule, cost, and risk.

In 1991, McDonnell Douglas sent a letter to the Navy program office explicitly stating its intention to place a priority on open communication and risk management, and to use IPPD to achieve its cost and schedule goals.⁶ The program's fidelity to these intentions and its overall success were marked by the award of the DoD's first Acquisition Excellence Award by Dr. Paul Kaminski, then the Under Secretary of Defense for Acquisition and Technology. Dr. Kaminski noted the program's use of IPTs and continuous sharing of information as key factors in the program's achievements.⁷ In the chapters that follow, this case study examines the program's IPPD management philosophy and the organizational structure and tools that support it.

⁵ F/A-18 Hornet Overtaking A-6, F-14, *Navy Times*, January 27, 1992.

⁶ *F/A-18E/F Integrated Technical Program*, MDC 91B0416, Volume II, Book 1, page iv.

⁷ F/A-18E/F Receives DoD Acquisition Excellence Award, PR Newswire Association, March 8, 1996.

Chapter 3. IPPD Principles

As described in the *DoD IPPD Handbook*, IPPD is designed to reduce costs and improve products by making early decisions that include inputs from stakeholders representing all elements of the system life cycle.⁸ By making decisions and changes early in the development phase, a program can reduce changes in the later and more expensive production and support phases of the program.

A program using IPPD also designs processes concurrently with the hardware that will be constructed or maintained by those processes. This concurrent development is intended to reduce costs by balancing the needs of the product and the processes associated with it.

Multidisciplinary teams are also a critical element of the IPPD process because they bring the various stakeholders together on teams, and because they provide the structure and accountability that allows proper tradeoff studies to be performed.

IPPD was critical to the success of the F/A-18E/F. Five key principles described in the *DoD IPPD Handbook* were essential to the effective implementation of IPPD on the F/A-18E/F program:

- **Customer Focus:** The primary objective of IPPD is to identify and satisfy the customer's needs better, faster, and cheaper. This is accomplished by including the customer in decision making and on multidisciplinary teams throughout the entire development process.
- **Concurrent Development of Products and Processes:** Processes should be developed concurrently with the products they support to ensure that the product design does not drive an unnecessarily costly, complicated, or unworkable process when the product is produced and fielded.
- **Multidisciplinary Teamwork:** Multidisciplinary teamwork is implemented through the use of IPTs. Teams comprise members from technical, cost, manufacturing and support functions and organizations, including customers and suppliers. Team members are empowered to make decisions for their respective organizations as well as keep them informed of the product and process decisions.

⁸ *DoD Integrated Product and Process Development Handbook*, Office of the Deputy Director, Systems Engineering in the Department of Test, Systems Engineering and Evaluation under the Office of the Under Secretary of Defense for Acquisition and Technology, Washington, DC, page 4. Available at http://www.acq.osd.mil/te/programs/se/ippd/ippd_pubs.html.

- **Proactive Identification and Management of Risk:** Risk management in support of IPPD includes the use of an organized, comprehensive, and iterative approach for identifying and analyzing cost, technical, and schedule risks, and instituting risk-handling options to control critical risk areas.
- **Integrated Information Environment:** A seamless information environment is used for requirements identification, planning, resource allocation, execution and program tracking over the product's lifecycle. This ensures that teams have all available information, enhancing team decision-making at all levels.

The following chapters discuss in more detail how each of these IPPD concepts were implemented in the F/A-18E/F program.

Chapter 4. Customer Focus

A key principle of IPPD includes a strong customer focus. The Navy Program Office has had a very active role throughout the entire F/A-18E/F life cycle. Every person from the contractor team with responsibility on the program has a customer counterpart with whom he talks daily. Customer involvement throughout the program's life cycle was evident during the "Twelve days of August" when requirements were being defined, and during Developmental Test and Evaluation (DT&E) with the Navy's involvement on the Integrated Test Team (ITT).

4.1 Twelve Days of August

In early August, 1991, Captain Craig E. Steidle, the Navy Program Manager for the F/A-18, held a "mini program review" of the proposed concept for the E/F. During the nine months prior to this review, teams from MDC, Northrop, General Electric, and the Navy had been working to define the configuration and high-level requirements for the E/F. When they came together for the review, it was clear that there was no agreement across teams. In the words of Jim Young, MDC's Integrated Product Team Manager:

Everybody was protecting their own rice bowls. The electronic warfare team wanted the best of the best. The low observables team wanted the most stealthy aircraft possible. The cockpit displays team wanted the very best and so on. The result was a weapon system that was over weight and over cost. Captain Steidle's conclusion during this review was that "We don't have a program here. What we have is a mess."

Larry Lemke was the MDC Vice President and General Manager of the F/A-18 at that time. He and Captain Steidle worked throughout the night outlining what they thought had to be the next steps if there was to be a viable E/F program. In Jim Young's words:

They decided to bring together people who were knowledgeable in all the many areas needed to define the E/F configuration and high-level requirements. So they convened a twelve-day meeting in St. Louis which began the following Tuesday and ended a week later on a Friday. The Navy had 35 to 40 people at that twelve-day meeting. There were also people from MDC, Northrop and General Electric. The idea was that at the end of the twelve days, they would either have a viable, affordable program or there would be no program.

At the beginning of the twelve days, Captain Steidle, along with Mike Sears, MDC's Deputy F/A-18 Program Manager, outlined for everyone the high-level objectives for the E/F. In comparison to the F/A-18C/D, the E/F had to have:

- more range (fly farther without refueling),

- improved survivability,
- more bring back (weight of stores that could be brought back and landed on a carrier),
- more carriage capability (could carry more bombs to a target), and
- more growth capability built in (extra physical space for future growth).

Captain Steidle instructed everyone at the meeting that these were the essential objectives against which tradeoffs would be made. However, because Congress mandated that the E/F could not exceed costs of the C/D by more than 25%, a different approach was called for. In Jim Young's words:

Before this meeting, the approach was to throw everything on the table and see what it cost. This time, affordability was an issue. Each group was tasked to think about what could be done differently. Given the high-level objectives of the E/F, we were asked to identify what has to be in the aircraft and what wasn't essential. We were told to question the *what* and the *how* of everything we did. What could we do to reduce weight and cost without impacting the high-level requirements?

During the twelve days, the teams would convene at the beginning and end of each day. Otherwise, each team worked their area. Over the twelve days they had to trade off weight, fuel capacity, volume, materials, the size of the radar cross-section (RCS), and cost. Operational analysis was going on throughout all of this in order to understand what was being gained at a system level with the changes that the teams were making. It was during this period that the concept for the Navy-contractor ITT during DT&E emerged. (The ITT is described in more detail in Section 4.2.) Northrop proposed changes to the bulkhead that resulted in a large weight savings. MDC proposed savings by going with a modest avionics upgrade in which 90% of the avionics were common with the C/D.

At the end of twelve days, the basic air vehicle requirements were in place. In Jim Young's words:

This was a focused effort to define the configuration so we could proceed to the next step. We came out of it with something that was good enough to be costed. And it brought everyone along at the same time (customer and contractor). We came out with a very clear direction. There was not much debate after that about what was in the aircraft. But we still had to guard against requirements creep.

In the fall of 1991, MDC, Northrop, and GE worked with Naval Air (NAVAIR) Systems Command to flesh out the requirements. As Jim Young described it:

We had a "spec jamboree." We broke into the same teams. We took the requirements and the configuration from the twelve days and used the C/D spec as a starting point. We took that specification apart and re-assembled

it to reflect the E/F we had defined. Where there were still disagreements, they were noted, and assigned to teams for resolution. Most of these were closed in the next couple of weeks. With this process, we were able to hammer out the important details of the E/F specification, include input from a wide range of stakeholders, and do it in a very short time

During these twelve days, the E/F changed from something that was "gold-plated" and over cost to something that represented an affordable evolution from the C/D. This was achieved by maintaining a customer focus and making appropriate tradeoffs. This set the stage for success.

4.2 Integrated Test Team

In addition to being involved during requirements analysis, the customer played an active role throughout the life cycle as illustrated by their participation on the ITT. Both the Navy and MDC personnel point to the structure of the ITT as an innovation of the F/A-18E/F program. It was a big step forward in facilitating more effective DT&E while at the same time saving money and time. ITT had its origins as a concept during the "Twelve days of August" (discussed previously in Section 4.1). It had been described in detail in the earlier IDA case study, and only a few additional remarks are needed. Jim Young expressed much of the value of the ITT from a cost perspective:

In the old days, DT&E took four years. The contractor flew the plane for two years, then the Navy flew it for two years, and then it was turned over for OT&E. With the ITT, both the Navy and the contractor fly their development tests and share data. DT&E has been reduced from four years to three years.

One important cost driver is how fast we can incorporate changes into the fleet. The lead OT&E test pilot is part of the ITT team and, hence, is participating in DT&E. The objective of DT&E is to test the weapon system against the specifications and especially to test the limits of the performance envelope. In contrast, the OT&E pilots don't care what the spec says. Their job is to evaluate the plane from the perspective of carrying out their missions. It's really been valuable to have the lead OT&E pilot on the ITT because he's been able to tell us what is critical about any performance problems from a mission perspective. We've made improvements already based on his input. This saves money because the earlier we make changes, the less expensive they are.

Jim Martin, MDC's F/A-18 Manager for Test and Evaluation, made the point that a great deal of time and effort went into defining the Navy's and the contractors' role and responsibilities for the ITT.

A Memorandum of Agreement (MOA) was used to define the responsibilities, structure, authority, and concept of operation for the ITT. The MOA was fleshed out with ITT Standard Operating Procedures. It

was approved by the Navy F/A-18 Program Manager, MDC's Vice President and NAVAIR functional organizations. The MOA took three years to produce. Every Navy slot in the ITT organization chart was originally filled by an MDC person. The Navy people are not just shadows. They are fully participating members of the test team.

The structure of the ITT illustrates how the customer needs are identified early and how the customer remains effectively engaged in the decision making process.

Chapter 5. Concurrent Development of Products and Processes

Concurrent development of products and processes, a second key principle of IPPD, refers to the “simultaneous development of the deliverable product and all of the processes necessary to make the product.”⁹ It is critical that the processes used to manage, develop, manufacture, verify, test, deploy, operate, support, train people, and eventually dispose of the product be considered during product design and development. Early integration of design elements can result in lower costs by requiring fewer costly changes late in the development process. Four examples from the F/A-18E/F program illustrate this principle: part count reduction, variability control, wing design, and flight control computer system. Each is discussed in more detail in the following subsections.

5.1 Part Count Reduction

The E/F airframe had 42% fewer parts than its C/D predecessor even though the airframe is approximately 25% larger. This part count reduction during design was achieved largely through consideration of high speed machining which allowed large complex parts to be machined from one piece of stock rather than assembled from a large number of smaller parts. By reducing part count, costs from many sources are reduced. This includes the obvious costs of part assembly, such as tooling, fastener installation, and inspection, as well as less obvious costs such as part tracking, and procurement.

The high speed machining process uses high spindle speeds and high feed rates, usually making shallower cuts than traditional machining. The shallower cuts and high feed rates prevent heat build-up that can cause thin parts to warp. This warping had previously made it impractical to machine the thin webs typical of aircraft structure, and therefore made it impossible to machine many of an aircraft’s large complex parts.¹⁰

To reduce part count and cost using this new machining technology, the MDC product teams tailored the design to take maximum advantage of the new technology. The IPTs searched the airframe for part count reduction opportunities, asking:

- Do parts move relative to each other?
- Do the parts need to be made from different materials?
- Do parts need to be removable?

⁹ DoD *Integrated Product and Process Development Handbook*, Office of the Under Secretary of Defense (Acquisition and Technology), Washington, DC, page 4. Available at http://www.acq.osd.mil/te/programs/se/ippd/ippd_pubs.html.

¹⁰ Proctor, Paul, High-Performance Machining Provides Efficiency Gains, *Aviation Week and Space Technology*, 24 August, 1998.

If none of these answers was yes, high speed machining, rather than multi-part assembly, was an option. The answers to these questions clearly required the inputs from strength engineers, maintainability engineers, producibility engineers and tooling engineers, among others. The IPPD philosophy and the IPT structure brought these experts together early in the design process, allowing these decisions to be made.

5.2 Variability Control

In another example of concurrently designing products and processes, the E/F program reduced costs and improved quality by creating production processes that reduced defects and rework. This reduction was achieved by creating the production processes and hardware designs simultaneously, and carefully analyzing the sources of variation using a process called Variation Simulation Analysis (VSA). IPPD and IPTs were critical to this analysis. For VSA to be used effectively, the tooling, manufacturing, assembly, and design engineers had to interact early in the development process, and make tradeoffs between their disciplines.

VSA analyzes an assembly by statistically combining the variations created in each phase of the manufacturing process. These variation sources include items such as the tolerances on the individual part drawings, the tolerances on the tooling drawings, and the capabilities of the various assembly operations. Each of these sources creates a mean result, and variation around that mean. A hole drilling operation, for example, may create a mean hole diameter of 0.250 inches, but will sometimes create 0.245 inch holes, while at other times creating 0.255 inch holes. When this variation is combined with tolerances in the tool that holds the part before assembly with the mating part, and with variation in the fastener diameter, a combination of random variables is created. VSA uses Monte Carlo simulation, which is a statistical combination of a series of random variations, to predict the percentage of time that the final assembly will fall within the requirements. A sample VSA output is shown in Figure 2 on the next page .

Figure 2 shows an assembly that will be out of specification limits over 12% of the time. Because the VSA analysis is done early in the design process, the IPT can evaluate corrective options ranging from revised tooling to revised tolerances on some component in the assembly to changes in the design. It is also possible to change the specified allowable variation because a multi-disciplinary team can evaluate the effect this change will have on system requirements. In a serial design approach, this analysis, if it was performed at all, would have occurred later in the process, perhaps only after production began and assembly problems surfaced. At that point, design changes are difficult and expensive.

When MDC had applied VSA as part of the IPPD approach, it found that roughly half of the original concepts required only minor optimization, while one quarter required changes to the tooling concept, and another quarter required changes to the hardware design. The process has certainly contributed to the overall ease of assembly that the E/F has experienced. In an example from the forward fuselage, it was estimated that VSA

reduced the number of hours correcting mismatches¹¹ in the forward fuselage by 80% compared to estimates extrapolated from F/A-18C/D production. Variation analysis and IPPD produced an assembly process that was estimated to require less than 20% of this amount. In another example, the estimated requirement for labor-intensive hand shimming was reduced 87%, from 75 linear inches in the original concept to less than 10 inches in the final design.

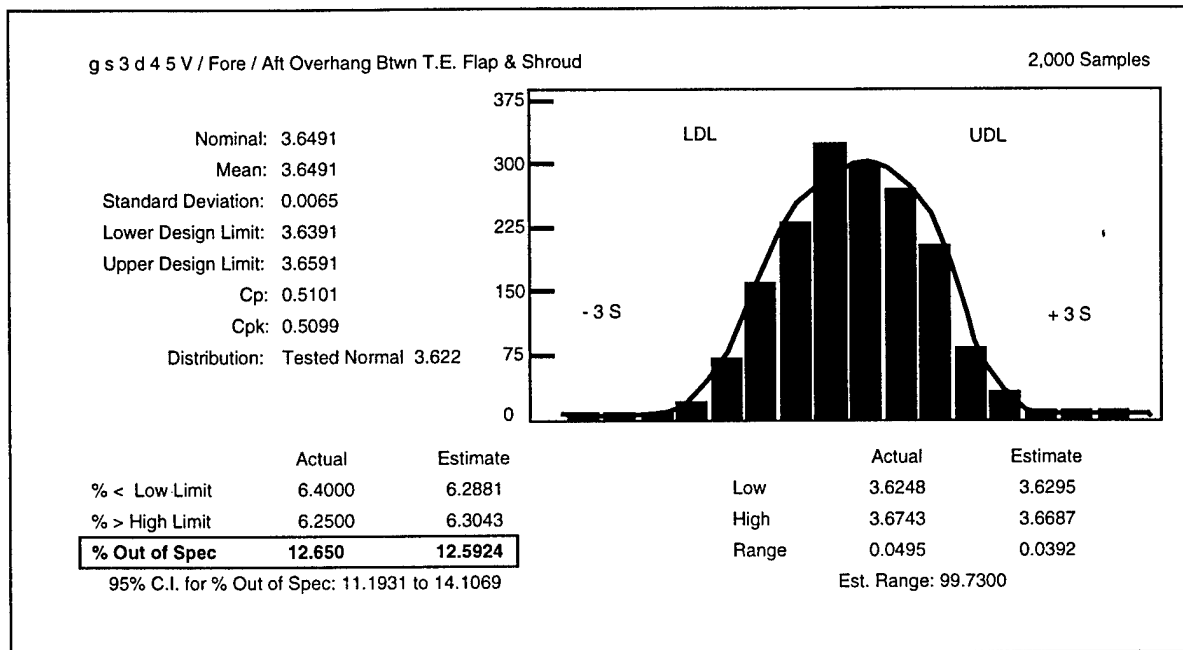


Figure 2. Sample VSA Output

5.3 Wing Design

The design of the E/F wing also illustrates the principle of concurrent development of products and processes and shows how a management philosophy is reflected in changes to hardware. The F/A-18C/D wing spars were machined in a process that required that the part be set in the tool four separate times, as shown in Figure 3.

The E/F wing IPT wanted to machine the spar using two setups (Figure 4) to save the cost of setups, save machine time, and prevent defects that setups can cause. This change had an effect on the design of the wing skin, which attaches to the spar in the wing assembly. In the original C/D wing, the spars were slaves to the skin design. The skin was refined to maximize strength and minimize weight. This process left many steps and contours in the skin that had to be matched by the spars. Removing the steps would add weight, but this weight turned out to be only a couple of pounds per shipset. The IPPD

¹¹ Mismatch means that two parts in an assembly do not line up as they are supposed to, so that where two surfaces should be touching in a joint, there is a gap. To fill in the gaps in the joint, the production people have to install shims.

management technique created the environment that encouraged this tradeoff study in the first place. The IPT organization put people from the weight, strength, and producibility disciplines on the team to make the tradeoff evaluation, and it gave the team authority to implement the tradeoff and final recommendation.

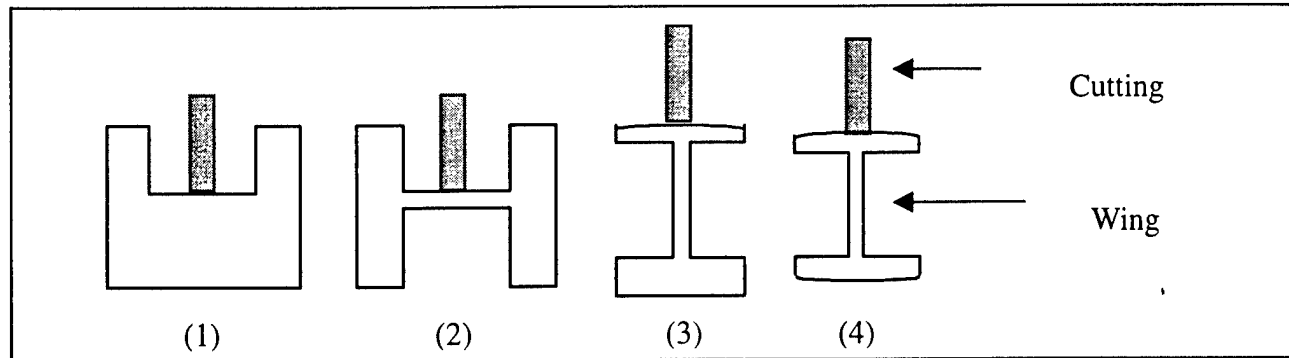


Figure 3. Process for Machining Wing Spars on the F/A-18C/D

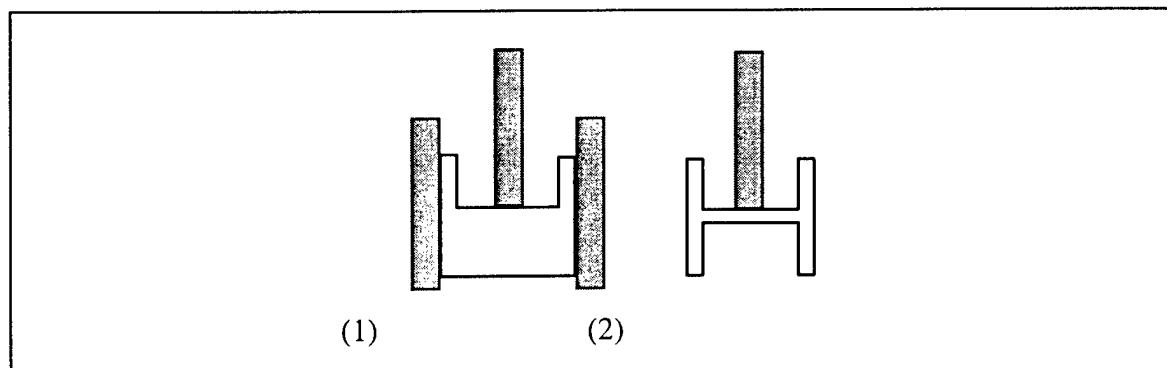


Figure 4. Process for Machining Wing Spars on the F/A-18E/F

In a further refinement of the wing skin, this team had to decide whether to manufacture the composite skins with hard tooling on the inside or on the outside surface. Composite parts are typically cured with one surface in contact with a hard tool, while the other surface is in contact with soft materials and a vacuum bag. The surface cured in contact with hard tooling will be smoother and have less variability than the bagged surface. The advantage of having the smooth surface inside the wing is that it improves the fit between the spars and skin, reducing shimming and the number of defects and rework. The advantage of having the hard tooling on the outside surface is that the smoother surface is desirable from a performance standpoint. Using IPPD and the IPT structure, the team determined that the hard tooling could go on the inside surface, and that careful tool design could accommodate the performance requirements on the outside surface.

These design tradeoffs contributed to a wing spar that costs 30% less to manufacture when compared to the cost of the C/D spar. In addition, the inner surface tooling and

reduced setup spars have contributed to E/F wing assemblies being completed with far fewer defects than their C/D predecessors.

5.4 Flight Control Computer System

The F/A-18 flight control computer system consists of hardware and software subsystems used to fly the plane. To develop this computer system, the F/A-18 E/F technology and product teams worked concurrently, and early in the life cycle, to reach an optimal solution for the overall program. One technology team in particular, the Flight Control Flying Qualities (FCFQ), worked extensively with the product teams and the other technology teams, including Aerodynamics, Structural Loads and Dynamics, and Materials and Structural Development teams.

The flight control computer system determines factors such as how the airplane responds to the pilot and how to keep the airplane stable, and provides for proper speed and direction. With other teams, the FCFQ team determined how best to move control surfaces such as the wing flaps or tail in response to the pilots commands. If the system requirement is to roll the plane 180 degrees per second under certain flight conditions, the FCFQ team would develop preliminary "control laws" or algorithms that eventually were implemented in hardware and software. But these initial algorithms were first evaluated by the other engineering teams to predict their overall effect. For example, the Structural Loads and Dynamics team analyzed the algorithm to predict the loads on individual pieces of the plane, ensuring that the airframe could withstand the loads. If the loads were outside of the desired range, this feedback was provided early to the FCFQ team who was given the opportunity to continually revise the algorithm before the hardware or software was actually developed. Numerous iterations and tradeoffs were made across the teams to generate optimal algorithms that would be responsive to the pilot while still satisfying the performance requirements for speed, weight, capacity, etc. The use of common databases and analysis tools—collectively known as Mod SDF (Modular Six Degrees of Freedom)—was essential for coordinating across the teams and achieving a balanced design. Section 8.3 describes Mod SDF in greater detail.

After the technology teams performed their initial analysis and incorporated feedback from initial simulations, the hardware and software requirements were documented for development. Only at this point were the algorithms formally documented in "change memos" which were controlled by Change Control Boards. The flight control requirements, for example, were controlled by the Flight Control Change Board. The interfaces were controlled by the Flight Control System Integration Team which consisted of representatives from all subsystems interfacing with the flight control computer. Consequently, the extensive analysis performed prior to formalizing the hardware and software requirements minimized both (1) the number of change memos controlled by these boards and (2) the number of actual changes made to the hardware and software systems after they had been developed.

Prior to the use of IPPD, this work was done sequentially moving from one product design group to another. As a result, delays and interdependencies were painful for the program, and there was little opportunity to change the control algorithms. In general,

the airframe was much heavier than desired: the Structural Loads and Dynamics team was typically at the end of the sequence and forced to compensate for control algorithms that required heavy reinforcements to meet the loads on the airframe. Today, an iterative approach is applied to the design of these control algorithms to provide early and continuous feedback across the technology and product teams.

Chapter 6. Multidisciplinary Teamwork

A third key principle of IPPD is use of multidisciplinary teamwork through IPTs. Teams comprising stakeholders, including customers and suppliers, are central to the IPPD process. By including stakeholders from various disciplines in the early phases of the design process, IPPD can reduce the number of changes later in the design process when these changes have a greater effect on both cost and schedule.

The early structuring of the organization into IPTs was an important and effective step in enabling IPPD on the F/A-18E/F program. These IPTs brought together a number of functional disciplines to design and produce the products and associated processes. The IPTs also performed the necessary tradeoffs that were required to build an affordable aircraft.

Assembling these teams early achieved more effective tradeoffs but required a funding profile that included higher early expenditures than those seen in previous programs—but with smaller expenditures occurring later. The E/F program's ability to deviate from previous funding profiles was a benefit of the Navy program office's close and cooperative involvement.

One benefit attributed to the use of IPTs on the F/A-18E/F was the more than a 50% reduction in the number of Drawing Change Notices or Engineering Orders per production drawing when comparing E/F's rate to A/B's rate:

- At first flight, the E/F had less than one Drawing Change Notice or Engineering Order per production drawing.
- The E/F's predecessor, the F/A-18A/B, had well over two changes per drawing at the same point in program.

The following sections describe the origin, composition, and the powers of MDC's multidisciplinary teams.

6.1 Evolution of the Team's Structure

Prior to the F/A-18E/F program, the C/D program was organized by functional area. The "hardcore" engineering disciplines (e.g., structures, aerodynamics, propulsion) came in first and designed the aircraft. Once the design was complete, the manufacturing engineers would get involved. Their job was to figure out how to tool, produce and assemble the multitude of parts called for in the design. Once they had completed this, the aircraft went into production.

Many of the problems that came up in production were the result of inadequate design definition.¹² And yet with this organization, the engineers who designed the aircraft were far removed—both physically and temporally—from the production team. In addition, the design of the aircraft was not done with ease of manufacturing or operational supportability as key issues.

Travis Durand, an engineer and current IPT leader said the following about the old way of designing aircraft:

For the C/D, engineering and production were in different buildings. The engineers would take a design to the manufacturing engineers and say “Go build this.” We’d toss the design over the fence.

6.2 Functional Integration and IPT Experimentation

In 1986, the Chief MDC Engineer on the F/A-18C/D program, Bill Norman, led an early experiment in functional integration by having the design engineers as part of the production team. These were called “Hornet Engineering Action Teams” or HEAT (i.e., an IPT). According to Travis Durand, MDC’s Level 4 Team Leader, F/A-18E/F Wing Team:

HEAT was pretty hit or miss. We struggled for approximately 18 months. Even though people were on the team, they weren’t really because the team leader didn’t control their raises. That didn’t happen until 1992 with E/F. The HEAT team controlled their day-to-day activities but the functional managers controlled their raises.

The current structure of IPTs began taking shape in 1991. Along with defining the team structure, a great deal of effort went into clearly defining the roles and responsibilities of each team along with the boundaries between teams. These were written up in the form of team charters. This set the stage for team leaders to be assigned responsibility, authority, and accountability for their product area, key concepts that will be revisited below. As the *DoD IPPD Handbook* points out, “the best way to minimize team misunderstandings is to document the team dynamics in a team charter for each IPT.” Figure 5 on the next page is an example MDC team charter.

6.3 Revised Team Structure

The organizational structure that was put into place on the F-18 E/F program corresponds to the product hierarchy as shown in Figure 6:

- At Level 1 is the F/A-18 Program Manager (Pat Finneran) whose responsibilities include the A/B, C/D, and E/F models. Also at Level 1 is the Deputy Program Manager for the E/F, Chuck Allen.

¹² Discussion with Chuck Allen, Boeing’s General Manager for the F/A-18 program, June 19, 1998.

**Establishment of the Office of Division Director of F/A-18 Program
Integrated Product Definition**

1. Purpose:

To establish the office and responsibilities of the F/A-18 Program Integrated Product Definition (IPD) Leader.

2. Mission:

To lead all aspects of Integrated Product Definition throughout the Define, Build and Support phases of the F/A-18 Program. As Co-Leader of the Shared Resources IPT Team, leverage and implement Enterprise Best Practices, and aggressively focus on reducing the cost of our products while meeting our contractual requirements.

3. Responsibilities:

The IPD Leader is responsible to the customer and program management for production definition, design, with shared responsibility for fabrication, assembly, delivery and fielded performance of the F/A 18 Weapon System.

This Position is also responsible for:

1. Allocation and flow down of Program cost, schedule, and technical requirements to the Shared Resources IPD teams
2. Providing leadership, and technical direction and integration to Shared Resources IPD teams. Manage performance to plan, risk assessments, trend analyses, and risk closure plans, as necessary.
3. Establishing and implementing management metrics to provide visibility of cost, schedule, and technical performance of the Shared Resources IPD teams.
4. Serving as the Principal engineering interface with the Naval System Command (Com NAVAIR Sys Com) and the Naval Air Warfare System Command (NAVAIR Sys Com) and the NAVAIR Program Office (PMA-265).
5. Partnering with the Production Operations to deliver quality, and affordable products on time and to identify opportunities to reduce cost.
6. Ensuring disciplined and common processes are implemented to meet contractual requirements.
7. Engaging and integrating internal, Built to Print, CFE and GFE suppliers into the IPD teams.
8. Serve as a member of the F/A-18 Leadership Team.

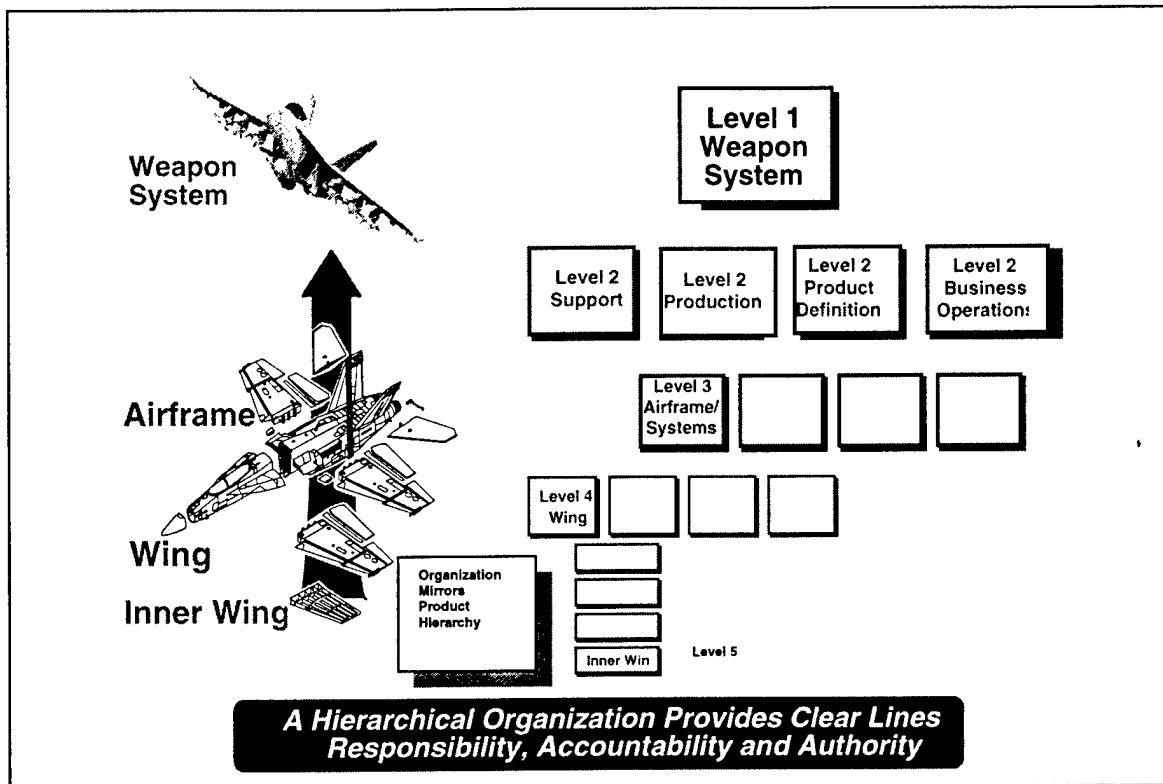
4. Accountability and Authority:

The IPD Leader receives authority from and is accountable to the Program Vice President for cost, schedule, and technical performance for all product definition deliverables. The IPD Leader is authorized to make decisions, allocate resources and delegate authority to accomplish program contractual requirements.

Submitted: _____
J.A. Young
Division Director
F/A-18 Program Engineering

Approved: _____
P.J. Finneran
Vice President/General Manager
F/A-18 Program

Figure 5. IPT Charter



Courtesy of the McDonnell Douglas Corporation.

Figure 6. Product Hierarchy vs. IPT Structure

- At Level 2, there is the IPT Manager, Jim Young. He has responsibility for the product definition activities. Also at Level 2 are the managers for Production, Support, and Business Operations.
- At Level 3, under Jim Young, there are the two major parts of the aircraft that MDC is responsible for: the Airframe subsystems and the Avionics/Weapons Integration.
- Level 4 (under Airframe subsystems) includes five teams: Wing/Horizontal Tail; Forward Fuselage; Hydromechanical/Mechanical; Armament, Crew, Electrical; and Support Equipment.
- Level 5 (under Wing/Horizontal Tail) includes three teams: Inner/Outer Wing; Wing Control Surfaces (leading, trailing edge flaps, and aileron); and Horizontal Tail.

This same structure forms the basis for the WBS. As will become clear below, one of the keys to the effective management of this program has been this correspondence between the product hierarchy, the organizational structure, and the WBS. Each of the teams, right down to Level 5, has allocations of dollars (which the team controls), weight,

reliability, maintainability, operations and support cost, electrical power, growth volume and performance. These measures are reported by each team on a regular basis (depending on the measure, weekly or monthly) and are described in Chapter 8, Integrated Information Environment.

The product and team structure are not static but continually evolving. As the F/A-18E/F moves from development into production, the product definition teams are becoming smaller while the production teams are growing. Both types of teams are multi-disciplinary. Travis Durand, the Level 4 lead for the Wing IPT stated:

The guy who is the team lead for the production of the wing was a member of my Product Definition Team six months ago. Now he has his own team and we sit next to each other in the production building.

The IPT structure changes with different phases of the life cycle, in keeping with the IPPD tenet of early and continuous life cycle planning. At the current time, the Engineering Manufacturing and Development (EMD) phase of the life cycle is almost finished while the production phase is ramping up. The Level 5 product definition teams will soon be absorbed into Level 4 at the same time that the production teams are expanding.

6.4 Empowerment of Teams

Empowerment of IPTs permits decision making to be driven to the lowest possible level commensurate with risk. Moreover, resources should be allocated to levels consistent with risk assessment authority, responsibility, and the ability of people. The team should be given the authority, responsibility, and resources to manage its product and its risk commensurate with the team's capabilities. The authority of team members needs to be defined and understood by the individual team members. The team should accept responsibility and be held accountable for the results of its efforts. Management practices within the teams and their organizations must be team oriented rather than structurally, functionally, or individually oriented.

The words often heard in reference to the F/A-18E/F team leaders are "responsibility, authority, and accountability." The team leaders are responsible for delivering the product and for maintaining frequent and open communication with their NAVAIR counterparts. They are given authority through control of their own budgets. They also write performance appraisals for their team members. Every team is allocated a budget for dollars, schedule, weight, and other relevant performance parameters such as power and cooling requirements. Accountability is achieved through the weekly reporting of these measures. Cost and schedule performance are tracked through weekly earned value reports down to the Level 5 teams.

Travis Durand, a Level 4 team leader, described the leaders' responsibilities this way:

Team leaders have to balance cost, quality, and schedule. They have to be good business folks as well as engineers. As a Level 4 team leader, I am running my own business. It's necessary to define the business boundary and what I need to run that business. We had casualties among the Level 4 and 5 leads in the early days. IPT leaders have to have a different set of skills.

Chapter 7. Proactive Identification and Management of Risk

The fact that the E/F was an evolution from the earlier C/D model lowered the risk over an entirely new design. In Jim Young's words, "We knew that cost, schedule and weight were do-able because we had experience on the C/D." Nevertheless, building an advanced fighter/attack aircraft is a complex undertaking where many things can go wrong.

IPPD enables an organized, comprehensive, and iterative approach for identifying and analyzing cost, technical, and schedule risks, and instituting risk-handling options to control critical risk areas. IPPD facilitates consideration of risks across functional areas and exploration of alternative design concepts. The *DoD IPPD Handbook* states that early planning and aggressive execution are key to successful risk management. This chapter describes MDC's risk management process and examples of how it is employed to mitigate risks associated with suppliers and hardware and software integration.

7.1 MDC's Risk Management Process

The F/A-18 program defines risk as an undesirable situation or circumstance that has both a probability of occurring and a potential consequence to program success. MDC's risk management process offers an organized systematic decision-making process that contains four key steps to reduce or eliminate risks:

1. Risk identification: What can go wrong?
2. Risk analysis: How big is the risk?
3. Risk planning: How can you reduce the risk?
4. Risk tracking: How are things going?

MDC uses a formal risk analysis process reflective of the process taught at DoD's Defense Systems Management College. Every team, all the way down to Level 5, has a risk management plan. Risks are identified and then analyzed in terms of their likelihood and consequence. Both likelihood and consequence are rated on a five-point scale. High and medium risks (Figure 7) are required to have a closure plan.

MDC also created the Systems Engineering and Integration organization to control risks and manage the requirements allocation process. The organization included a Level 2 manager, and drew heavily from the lower-level product teams. This team took the requirements defined in the system specification and broke them down for allocation to the product teams. The specification for aircraft weight requirement, for example, would become weight requirements for the wing team, the forward fuselage team, and the vertical tail team. All system requirements, including survivability, reliability, cost and schedule, were allocated in this way. By the time the program reached Preliminary Design Review, 3,000 specification paragraphs had been allocated to the product teams.

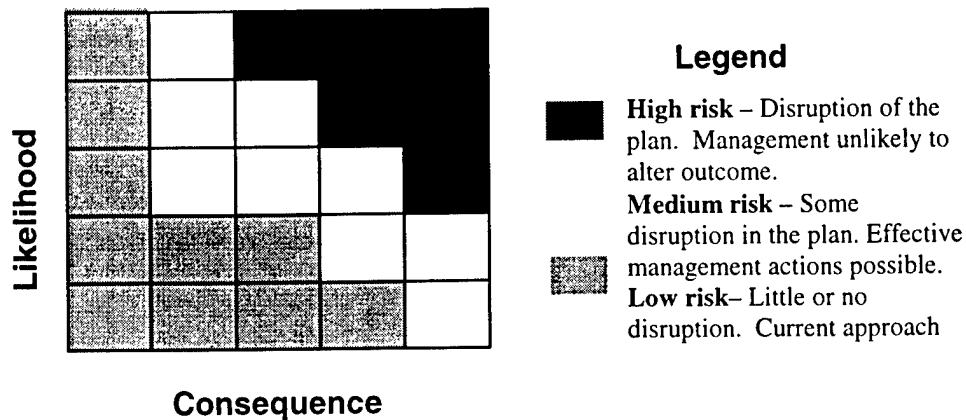


Figure 7. Risk Management Matrix

Perhaps the most important aspect of the E/F's risk management program is the attitude toward risk that permeates the entire program, on both the contractor and on the government side. Henry Harchburger, Level 3 IPT Leader for Airframe Technology, described this attitude as follows:

Our definition of good management is recognizing problems and asking for help early on. Anybody can define a risk. It's okay to have risks, we just need a risk mitigation plan. There are three things that are necessary for an effective risk management system. First, you want to identify potential problems early. Secondly, you've got to have management that doesn't shoot the messenger. It's critical that your customer has the same opinion. You have to have people who don't go ballistic when they have a problem. And third, you've got to have management that will provide help when asked. The person at the top has got to have that attitude. And in asking for help, you have to be able to say what you need.

7.2 Supplier Risk

An example of MDC's proactive approach to risk management is given by its handling of the supplier of the landing gear. In November of 1997, the main landing gear supplier was on the critical path of being able to deliver the first of the low-rate initial production (LRIP) aircraft for operational test. The scheduled install date for the gear was June 1998. In the words of Theresa Carr of MDC:

We knew that this was a schedule risk since the landing gear was on the critical path. We helped the supplier talk to their suppliers to ensure that they had the parts they needed. Our management reports helped us stay on top of this because it does network projections. The problem was

addressed and tracked to closure, and an alternative installation plan developed and implemented to support delivery.

Because a team could not exercise its decision authority properly without knowing what its specific requirements were, rigorous allocation of system requirements was essential to effective risk management. MDC's philosophy dictated that decisions were to be pushed down in the hierarchy (empowerment) while progress was to be reported back up using metrics that were common throughout the program (risk management). Obviously, the team's ability to communicate its progress to upper management also depended on a clear understanding of goals and expected progress. Without this reporting, a formal system of risk identification would be impossible.

7.3 Hardware and Software Integration Risks

Hardware and software integration risks were addressed early and throughout the life cycle by MDC. During the early stages, the teaming arrangement was re-evaluated to give MDC more control of the software and the integration activities. Documentation and verification processes were also defined early in the life cycle to support integration. When risks were identified throughout the life cycle, multidisciplinary risk management teams were established to explore alternative design concepts, evaluate their impact, and to select the most effective solution. Another factor contributing to successful hardware and software integration includes the integrated information environment described in Chapter 8.

During development of the F/A-18 A/B and C/D, a decision was made in technical coordination meetings with MDC, Navy, and Lockheed Martin to procure the flight control computer hardware and software from Lockheed Martin. For the E/F, however, this risk was reevaluated early in the life cycle when the teaming arrangements were being negotiated. There was a formal "make versus buy" decision to determine if it would be more effective to bring the software in-house. MDC analysis identified that bringing the software in-house would be cheaper with a quicker turn-around and would offer more flexibility. Thus, the decision was made for MDC to develop the flight control computer software for the E/F, and Lockheed Martin to supply the hardware.

Hardware is not generally thought of as "the problem" during integration because most hardware problems are fixed by developing software work-arounds. And because the original supplier often found the software changes to be out of scope compared to the original estimates used to bid the contract, MDC had difficulty negotiating numerous software changes with the supplier. It became easier for MDC to implement the changes in-house than to develop formal purchase orders and change orders with the supplier to implement changes. In addition, MDC wanted to control software to control the cost and schedule of integration. Examples of MDC's effective control of software include the "weight on wheels" problem and "side slip" measurement. In both cases, MDC benefited from the flexibility of having software developed in-house and exploring alternative design concepts to resolve system integration risks.

Weight on wheels switch. The “weight on wheels” example refers to a switch inside the landing gear that indicates if there is any weight on the airplane’s wheels, used to designate whether the airplane is in the air or on the ground. A problem arose in the weight on wheels switch when the brake was applied to the wheels after take-off but before the wheels were inside the wheel well. The brake caused a strut in the landing gear to compress, which, in turn, tripped the signal indicating there was weight on wheels for a slight moment even though the plane was in the air with no weight on the wheels. There are several functions whose operation are dependent on whether the plane is in the air or on the ground. For example, when the plane is on the ground the heater used for anti-icing does not use heat since there is limited air movement. But when the plane is in the air, the heater must be very hot to be effective with increased air movement. If the switch inaccurately indicated the airplane was in the air, the anti-icing heater could overheat a grounded plane. Other examples include the flight control computer algorithms whose operation are also dependent on whether the plane is in the air or on the ground. The slight moment when the switch registered an inaccurate reading made a difference: the pilot was prevented from using the “nose down control” to land the airplane because the switch inaccurately identified that the plane was already on the ground.

To address the problem with the weight on wheels switch, MDC established a multidisciplinary risk management team with representatives landing gear, flight control, and management. Both hardware and software solutions were considered. The hardware solution involved moving the switch away from the strut but this had added cost plus uncertainty: the new location could introduce new problems (e.g., could the bounce the airplane experiences on the runway inappropriately trigger the switch in the new location?). The leading software solution included the development of an algorithm that identified under what conditions the weight on wheel signal was invalid. For example, “if the weight on wheels occurred shortly after take off, then ignore the signal.” The risk management team determined that the most cost-effective solution was to implement the new software algorithm.

Side slip measurement. The second example of how the F/A-18 program benefited from MDC’s control of software was the calculation of the side slip measurement. Rather than measure the head-on effect of air current, side slip measures the angle air makes with the side of the airplane which affects how the airplane flies. An airplane flies better if it accounts for side slip, though historically this measurement has been too difficult to obtain. The F/A-18 E/F, however, made this evolutionary improvement. MDC established a risk management team to evaluate hardware and software solutions. The hardware options required new sensors to be mounted on the airplane to measure side slip, whereas the software solutions took advantage of existing sensors to calculate side slip indirectly with revised control laws. While the leading software solution was less accurate, it was determined to be accurate enough and was less costly to implement and maintain than new hardware sensors. As a result of implementing the side slip measurement in software algorithms, the E/F airplane flies better at high angles of attack, thus eliminating the departure mode called “falling leaf” which is commonly experienced in the F/A-18 A, B, C, and D. This occurs when the airplane goes out of control like a falling leaf and rocks side to sides as it falls.

Up-front” documents and verification. In addition to maintaining control of software development, integration risks were controlled by having “up-front” documents that account for integration into the system and “back-end” processes that verified the subsystems are working together. The up-front documents decomposed the system requirements into hardware and software specifications, designs, and interfaces. The back-end verification processes tested each hardware and software subcomponent as well as the integrated components at the system level. Laboratories and simulators are used to perform the unit and integrated tests (refer to Section 8.3 for more details). The following table lists the key documents and processes contributing to risk management of hardware and software integration.

Table 1. Key Documents and Verification Processes

Up-Front Documents	Back-End Verification Processes
System and Subsystem Specifications	Shop Replaceable Assembly Testing
System Design Document	Computer Software Unit Testing
Interface Control Documents	Replaceable Assembly Testing
Interface Definition Documents	Computer Software Component Testing
Hardware Description Documents	Hardware Configuration Item Acceptance Testing
Critical Item Development Specification	Computer S/W Configuration Item Acceptance Testing
Software Requirements Specification	Hardware/software Integration
Assembly Drawings	Avionics Integration Verification Testing
Shop Replacement Assembly Fabrication	Aircraft Ground Tests
Software Design Document	Aircraft Flight Tests
Computer Software Unit coding	
Test Plans	

Overall, hardware and software integration is viewed as a major risk to the F/A-18 program. But measures are taken to identify and analyze the risks and to implement risk mitigating solutions. MDC uses in-house software development to help control integration risks as well as up-front documents and back-end processes.

Chapter 8. Integrated Information Environment

Another key principle of IPPD is the establishment of a management system that relates requirements, planning, resource allocation, execution, and program tracking over the product's life cycle. MDC did this by creating HornetWEB, IMICS (Integrated Management Information Control System), and Mod SDF (Modular Six Degrees of Freedom) to manage the E/F program.

MDC used commercially developed and widely distributed technologies that were not available when the C/D was developed. For example, electronic mail, nearly unknown at the time of the F/A-18C/D development, was used very heavily in the E/F program, with some people receiving as many as 100 messages a day. Because team leaders had to communicate with people from many disciplines, and because these team members were in St. Louis (MDC), Los Angeles (Northrop), Washington (NAVAIR), China Lake (NAVAIR), and traveling all over the world, this communication was essential to an effective IPPD process.

This chapter describes the three MDC proprietary integrated information systems: HornetWEB, IMICS, and Mod SDF.

8.1 HornetWEB

The HornetWEB is a secure information system hosted on MDC's intranet and accessible by MDC, the F/A-18E/F subcontractors, and the Navy program office. HornetWEB helps to provide all stakeholders real-time access to unclassified technical and business information. It is used to enhance workflow management, system development, action item coordination, and electronic document sharing. As a secure system, the data is protected with adequate firewalls, data integrity, and security safeguarding programs.

Specifically, the HornetWEB supports sharing of data from both a user's perspective as well as an author's perspective. With the aid of a network browser and document viewer, users have access to integrated databases and documents that contain the types of information depicted in Table 2 on the next page.

The HornetWEB content manager, Kenneth Kepchar, said the following about the system he helps to maintain:

The HornetWEB provides logistic information including publications. Users for example can now query databases on the HornetWEB intranet to identify what support is required for a particular F/A-18 engine. The user would receive lists and photographs of the engine's support gear. In the old days this information was contained in 12-inch thick binders. HornetWEB now puts this information on-line, making the data more

accessible, easier to maintain, and more current. Logistic support is now one of the web sites most often queried.

Table 2. Example of HornetWEB Process Links

HornetWEB Sites	Examples
Business Acquisition	Contract documents, specifications, new product development, Navy programs, international programs
Program Management	Configuration management, data management, human resources, program directives, measurement program, metrics
Systems Engineering	CALS/CITIS information, reliability and maintainability, survivability, risk management, supportability assurance, Management Plan, Readiness Program
Product Development	IPTs, controls and displays, flight controls, transition
Verification	Flight limitations, operational evaluation preparedness
Production	Quality assurance, supplier management and procurement, training systems, variability reduction
Product support	Support engineering, publications, technical manual, ILS management team interface, maintenance engineering investigations, supportability assurance readiness program

Key: CALS Continuous Acquisition and Life-Cycle Support
 CITIS Contractor Integrated Technical Information Service
 ILS integrated logistics support

HornetWEB also provides authors of data files access to standard development tools including editors, document converters, databases, compilers, and other utilities. This information system has helped to facilitate IPPD practices by making key data accessible across the F/A-18 program.

8.2 IMICS

In addition to the HornetWEB, there is probably no technology or software that had more impact on the program than IMICS. Whenever F/A-18E/F success factors are discussed by either contractor or government managers, IMICS is inevitably near the top of the list. In the program's first award fee letter from the government, the system was cited as a major strength of the program. The team that created the system has received the highest awards at both the company and corporate levels within MDC. Most importantly, the system is widely noted as being critical to the program's successful pursuit of two key IPPD tenets: open communication and rigorous risk management. These priorities were demanded by the Navy in response to the failure of the A-12 program, and MDC formally promised them from the very start of the F/A-18E/F program.

To meet these objectives of open communication and rigorous risk management, high-level program officials both inside and outside of MDC had to effectively monitor the program and communicate its progress even while decision authority was being pushed to the lower-level IPTs. This was accomplished by first allocating the requirements as far down as Level 5 teams, as described previously in this study. After allocating the requirements, the teams had to be able to systematically measure their progress against these requirements and report this progress to management. The system had to be constructed so that the measurements were easily understood by a wide range of people no matter what part of the program the reports described.

The *DoD IPPD Handbook* recommends that IPTs develop technical and business performance measurement plans with appropriate metrics to monitor the effectiveness and degree of anticipated and actual achievement of technical and business parameters. F/A-18E/F IPTs created specific metrics for schedule, cost and risk status, as well as for technical performance. Schedule and cost results were reported weekly while supportability and technical performance parameters—such as reliability, maintainability, weight, and RCS—were reported monthly. IMICS provided snapshots in time as well as trend analysis. Separate charts also allowed IPT leaders to “ask for help” when some performance parameter was not progressing as planned.

Early in the program, the customer criticized MDC for including too many subjective measures of progress in their program reporting. MDC responded aggressively, and within several months had created objective measures for 97% of the work packages of longer than 14-weeks duration. Overall, less than 20% of the tracked items use level of effort as a measure of progress.

The objective measures MDC created reached impressive levels of detail, often becoming templates that were to be used by all teams, to ensure consistency of reporting. For example, the template to measure the progress of a structural assembly layout (ALO) was two pages long. It listed 26 separate items that must be completed before the ALO could be considered 20% complete, and 28 more that must be achieved to reach the 70% complete milestone. Armed with their allocated requirements, and templates for reporting progress against the requirements, IPT leaders knew what was to be reported every week, and how their performance was being measured.

IMICS made this reporting useful to management by pushing information up the organization in a system that was consistent in its presentation, but flexible in the level of detail presented. IMICS took data for all metrics and at all levels, and rolled them up at whatever level a manager wished to see them. If interested in weight, for example, a manager could see the overall aircraft weight progress and trends. He or she could then “drill down” to lower levels and see how weight was progressing in the Level 4 wing team, or even in the Level 5 control surfaces team. Additional IMICS measures include cost and schedule performance indices as follows:

- Budgeted cost of work scheduled
- Budgeted cost of work performed
- Actual cost of work performed
- Cost variance
- Cost performance index
- Budget at completion (dollars)

- Schedule variance
- Estimate at completion (dollars)
- Schedule performance index
- To complete performance indices

Managers at MDC and in the government had access to IMICS information at all levels of granularity as it was updated each week. Items falling behind their goals were easily identified, and progress against corrective action was easily tracked. When an item demanded upper level attention, Captain Joseph W. Dyer, the government program manager, and Mike Sears, the MDC program manager, could each bring the same data up on their screens as they discussed the problem. In more routine situations, the metrics and the presentation charts provided a ready format for the weekly management meetings held at MDC and for progress reports to officials outside.

Because IMICS organized a large amount of data into usable form, and was widely used and distributed both within and outside the government, it made the progress of the program understandable to a wide number of people. This wide communication, in turn, allowed the teams to effectively identify and address areas that put the program's objectives at risk. Because IMICS was so effective, it has been widely praised for its contribution to the F/A-18E/F, and is now being applied to other MDC programs.

8.3 Mod SDF

MDC used common databases and analysis tools, known collectively as Mod SDF, to facilitate the exchange of information across the product and technology teams to produce balanced requirements and designs. Table 3 contains a list of the Mod SDF databases and tools used by these engineering teams.

Table 3. Mod SDF Databases and Analysis Tools

Mod SDF	Technology Teams			
	Aerodynamics	Flight Control Flying Qualities	Structural Loads & Dynamics	Materials & Structural Development
Databases	Aero Database	Control Laws	Loads Database	Materials Database
Analysis Tools	Mission Performance	Flying Quality Criteria	Design Loads	Design Allowables
	Carrier Suit Performance	Control Laws	Dynamic Environment	Composite Allowables
	Weapon Separation Requirements		Aeroelastic Stability Requirements	Full Scale Test Requirements

In addition to the tools listed in Table 2, the technology teams relied heavily on the use of simulations supported by Mod SDF to analyze the requirements, software code, and the integrated subsystems. As in the case of the flight control computer system,

simulations were used to conduct several levels of testing to ensure the Assembly code and flight hardware were operating correctly.

- First, fully automated software testing was performed to compare the results of the Mod SDF simulated software with that of the Assembly code operating in the Flight Control Computer. The software developers did this to ensure that their Assembly programs produced the same expected results as the simulations which were used to optimize the engineers' algorithms.
- Second, the flight control computer with the Assembly code was tested together with the mission computer and with simulations of other subsystems in an extensive series of manual and automated tests.
- Third, this same configuration was tested in the Manned Flight Hardware Simulator.

Overall, these simulations were performed with progressing levels of difficulty and helped to test the integrated subsystems in a dynamic, interactive environment.

Chapter 9. Conclusions

The contractor reported that the F/A-18E/F program's low-risk philosophy and cost consciousness contributed to its success in achieving or exceeding cost and schedule goals. The EMD program met the budgeted goal of \$4.88 billion (Fiscal Year 1990 dollars). The first flight occurred a month ahead of schedule, and was performed with an air vehicle that was well below its specified weight. The flight test program had completed 3,000 hours and 2,000 flights by June of 1998, and has completed 75% of the EMD program.¹³ The program has entered LRIP, with 62 aircraft under contract, and the first production aircraft scheduled for delivery in January 1999.

Though the program is still in EMD, MDC has reported projected improvements in the reliability and maintainability measures of the F/A-18E/F as compared to its predecessors. In response to Fleet questions during a 1998 visit to the Navy aircraft carrier, the USS *Abraham Lincoln*, senior MDC officials reported to the Navy the following:

- The projected reliability or Mean-Flight-Hours-Between-Failure of the E/F model compares favorably with the current F/A-18C/D fleet with an improvement of up to 25%.
- The "Organizational" Level Scheduled and Unscheduled Maintenance Man Hours/Flight Hour is expected to improve by over 40% when compared to the current C/D Fleet.

The F/A-18E/F design reflects the multi-role demands that will be placed on it and the low-risk programmatic environment in which it was created. The contractor reported improvements over the F/A-18C/D in nearly every measure, but it is an evolutionary aircraft with less ambitious goals than the failed A-12, A-X, and NATF. Examples of E/F improvements include:

- Improving the F/A-18C/D's range by between 20 and 50%, depending on the mission profiles and store combinations used for comparison.
- Improving survivability relative to the C/D by employing limited RCS control features, by adding advanced defensive systems, and by reducing the aircraft's vulnerable area.
- Providing 11 stations for carriage of weapons, fuel, and other stores, compared to the C/D's 9 stations.

¹³ For more information, see the Hornet Hyperlink Web site at <http://pma265.navair.navy.mil/reports/1998/980701.html>.

- Providing the capability to bring 3,000 pounds more of these stores back to the carrier, greatly improving mission flexibility.
- Providing 17 cubic feet of empty internal volume to accommodate additional avionics packages or other upgrades, allowing for future capability improvements.

MDC acknowledges five principles of IPPD as being largely responsible for the F/A-18E/F program's success as follows.

Customer Focus

As seen during the "Twelve days of August," the customer and the contractors worked together to define requirements and make necessary tradeoffs. Communications between MDC and the customer were frequent and open, including daily contact. The F/A-18E/F became an affordable evolution from the C/D and not another gold-plated program.

Concurrent Development of Products and Processes

This case study includes several examples of the concurrent development of product and processes. By tailoring the design of the E/F to take maximum advantage of improved manufacturing processes, the E/F consists of 42% fewer parts than the C/D even though it is 25% larger. Reducing the number of parts reduced costs. Moreover, by creating production processes and hardware designs simultaneously and carefully analyzing the sources of variation in the process, the F/A-18E/F program was able to reduce production costs and create production processes that reduced defects and rework. As an example, concurrent design tradeoffs resulted in E/F wing spars of higher quality and costing 30% less than the C/D wing spars. Numerous iterations and early tradeoffs made while designing the flight control computer system resulted in fewer requirements changes and change memos.

Multidisciplinary Teamwork

Several factors contributed to successful multidisciplinary teamwork on the F/A-18E/F program. Dollars, schedule, and technical parameters were allocated down to Level 5 in the WBS. In addition to having control over their own budgets, team leaders had the appropriate authority to get jobs done. Weekly reporting of metrics kept teams informed and accountable. Organizational structure mirrored product structure, with the result that the product was broken down into small enough pieces to be developed by a single team. Finally, skills of the team leaders were critical to the success of teams.

Proactive Identification and Management of Risk

The fact that the E/F evolved from the C/D lowered the risk of the program from the outset. However, proactive identification and management of risk were still essential to

the ultimate success of the program. Proactive identification was accomplished through the overarching management philosophy of recognizing problems early on and asking for help. Weekly reporting was instrumental in this process. Once system requirements were allocated to teams, teams used MDC's formal risk management process to develop risk management plans that identified risks and then analyzed them in terms of their likelihood and consequence. Included in the risk management plans were alternative design approaches evaluated by multidisciplinary teams to identify the most effective solution. This process was applied to the analyses of the weight on wheels switch and the side slip measurement.

Integrated Information Environment

The integrated information environment, examples of which were the HornetWEB, IMICS, Mod SDF, and electronic mail, was critical to the program's success by enabling open communication and rigorous risk management. HornetWEB, a secure information system, enhanced workflow management, system development, electronic document sharing, and scheduling and milestone planning by making key data accessible across the F/A-18E/F program. IMICS was a standard system for measuring and reporting progress at all levels. Mod SDF, a collection of common databases and analysis tools, was used to facilitate exchange of engineering information across development teams. Moreover, managers at all levels of both MDC and the government had access to HornetWEB, IMICS, and Mod SDF.

* * * * *

For additional information concerning IPPD and DoD acquisition case studies, refer to the Office of the Deputy Director, Systems Engineering in the Department of Test, Systems Engineering and Evaluation under the Office of the Under Secretary of Defense for Acquisition and Technology.

The Office of the Deputy Director, Systems Engineering can be reached at the Pentagon, Room 3D-1075, Washington, DC 20301-3110, (703) 695-2300, as well as through its Web site at <http://www.acq.osd.mil/te/programs/se/index.htm>

Chapter 10. Discussion Items

The following questions are provided to stimulate the discussion and understanding of the use of IPPD on the F/A-18 E/F program. Appendix A contains examples of responses to each question.

1. What technique was used to ensure stakeholder issues were addressed early in the life cycle?
2. How did the F/A-18 program benefit from the Integrated Test Team?
3. How were benefits achieved from concurrent development of products and processes?
4. How did the F/A-18 program structure its Integrated Product Teams?
5. What barriers did the program run into when establishing the IPT structure and how did the program resolve them?
6. How did MDC management empower the IPT leaders and team members?
7. How did the composition of the teams change throughout the life cycle?
8. What are the four key steps used in the proactive risk management program?
9. What analytical and management techniques were used to control risk?
10. How did empowerment contribute to the risk management practices?
11. How did the F/A-18 ensure everyone had immediate access to the most current information for decision making?
12. What methods were used to support hardware and software system integration?
13. What approach did the F/A-18 take to monitor and report progress?
14. Given the IPPD approach was used on the F/A-18 E/F program, what distinguishes the program as a management success?

Appendix A.

Example Responses to Discussion Items

Chapter 10 of this paper contains a list of questions designed to stimulate discussion among students of the DoD acquisition process. Following are example responses which can be used to initiate or guide the discussion.

1. *What technique was used to ensure stakeholder issues were addressed early in the life cycle?*

Early in the FA-18E/F life cycle, during the "12 days of August," stakeholder teams from MDC, Northrop, General Electric, and the customer (Navy) worked together to define requirements and analyze tradeoffs. This was done against a backdrop of high-level objectives that included more range, better survivability, more "bring back," more carriage capability, more growth capability built in, and a Congressional mandate that cost of the E/F not exceed cost of the C/D by more than 25%.

2. *How did the F/A-18E/F program benefit from the Integrated Test Team?*

The Integrated Test Team benefited the F/A-18 program through early life cycle focus, concurrent development of products and processes, and customer focus. An early life cycle focus enabled the ITT to reconsider traditional testing practices and redesign them so that the contractor and government tested the aircraft concurrently. This new process was more effective in that it reduced DT&E from four years to three years. Moreover, early involvement of the OT&E pilot reduced costs because the OT&E pilot was able to recommend changes earlier when they were less expensive to make.

3. *How were benefits achieved from concurrent development of products and processes?*

MDC reported that concurrent development of products and processes resulted in lower costs and improved quality due, in part, to a reduction in the number of parts, optimization of the wing spar machine process, and use of Variation Simulation Analysis. Specifically, the E/F airframe had 42% fewer parts than the C/D, which reduced costs of part assembly, such as tooling, fastener installation and inspection, as well as part tracking and procurement costs.

Streamlining the wing spar design to require fewer cuts also reduced the cost of setups, saved machine time, and prevented defects that setups can cause.

Finally, by creating the production processes and hardware designs simultaneously, and carefully analyzing the sources of variation using Variation Simulation Analysis, the E/F program was able to reduce defects and rework which, in turn, reduced costs and improved quality.

4. *How did the F/A-18 program structure its Integrated Product Teams?*

The F/A-18 program structured its Integrated Product Teams according to the Work Breakdown Structure (WBS), a product hierarchy consisting of five levels. By doing so, the relationship between IPTs was clear, and team members had visibility for how their IPT contributes to the overall program. Overall team membership was based on multifunctional, multidisciplinary, and stakeholder involvement.

5. *What barriers did the program run into when establishing the IPT structure and how did the program resolve them?*

The initial IPT structure was unsuccessful because it lacked authority and accountability. For example, team leaders did not control members' raises. This was resolved by defining and documenting team structure, roles, and responsibilities in team charters.

6. *How did MDC management empower the IPT leaders and team members?*

MDC management empowered IPT leaders and team members by establishing team charters that define the role and responsibility of each team as well as boundaries between teams. In this way, team leaders were assigned accountability, authority, and responsibility. Each team was allocated a budget for dollars, schedule, weight, and other relevant performance parameters. Accountability was achieved through the weekly reporting of these measures. This empowerment of IPTs permitted decision making to be driven to the lowest possible level commensurate with risk.

7. *How did the composition of the teams change throughout the life cycle?*

IPTs evolved throughout the life cycle to ensure continuous focus on the life cycle and appropriate stakeholder involvement. For example, as the product moved from development into production, the number of members on the IPT representing requirements definition decreased but the number of members representing production increased.

8. *What are the four key steps used in the proactive risk management program?*

- (1) Risk identification: What can go wrong?
- (2) Risk analysis: How big is the risk?
- (3) Risk planning: How can you reduce the risk?
- (4) Risk tracking: How are things going?

9. *What analytical and management techniques were used to control risk?*

To help control risk, MDC used the analytical techniques of system decomposition and a risk management matrix categorizing likelihood and consequences of each risk. One management technique was to create the Systems Engineering and Integration organization to control risks and manage the requirements allocation process.

10. *How did empowerment contribute to the risk management practices?*

By empowering individuals at all levels to recognize risks and to ask for help early on, MDC created an environment open to risk identification. Management's attitude was that effective risk management depends on identifying potential problems early, not penalizing people for identifying risks, and providing help when asked.

11. *How did the F/A-18E/F ensure everyone had immediate access to the most current information for decision making?*

HornetWEB, a secure information system on MDC's intranet and accessible by the MDC teams, the F/A-18 subcontractors, and the Navy program office, provided all stakeholders with real-time access to technical and business information. It enhanced workflow management, system development, action item coordination, and electronic document sharing. It also provided users with standard development tools such as editors, document converters, databases, compilers, and other utilities.

12. *What methods were used to support hardware and software system integration?*

The purpose of integration is to ensure system elements function together as a whole to achieve the program's requirements. Integration primarily involves identifying, defining, and controlling subsystem interfaces as well as verifying system functions. On the F/A18-E/F, integration activities began early when all engineering disciplines could influence the requirements and interfaces and define "up-front" documentation and "back-end" processes. System interfaces and requirements were formally documented and controlled through Change Control Boards. In the case of the Flight Control Computer, integration was further supported with the formation of a Flight Control System Integration team consisting of representatives from all subsystems interfacing with the Flight Control Computer.

With a change in the original teaming agreement, MDC sought control of software development to better control the cost and schedule of integration. MDC benefited from having the flight control computer software developed in-house because it also provided the flexibility to evaluate alternative design approaches and to implement the most effective solutions which were usually done with added software as opposed to hardware (e.g., weight on wheels switch, side slip measurement).

In addition, Mod SDF provided an integrated information environment facilitating the analysis and optimization of requirements across the engineering teams. In the case of the flight control computer system, numerous iterations and tradeoffs were made between the engineering teams to ensure that all system-wide design impacts were considered early in the life cycle and that the tradeoffs resulted in the best solution for the aircraft as a whole.

Verification was done with extensive use of analysis and simulation models such as those supported by the Mod SDF. Simulations were used to evaluate the Flight Control Computer, Mission Computer, and other subsystems in an extensive series of manual and automated tests. Fully integrated hardware and software systems were also used to perform manned flight simulations with pilots.

13. What approach did the F/A-18E/F take to monitor and report progress?

Once the F/A-18 system was decomposed, and requirements were allocated as far down as Level 5 of the WBS, the Integrated Management Information Control System (IMICS) was critical to measuring and reporting progress to management. IMICS took data for all metrics and at all levels, and presented them at whatever level of granularity a manager wished to see them. It thus facilitated accurate progress measurement, open communication, and rigorous risk management on the F/A-18 program.

14. Given the IPPD approach was used on the F/A-18E/F program, what distinguishes the program as a management success?

As reported by the MDC contractor, the F/A-18E/F was able to meet its budget ahead of schedule with improved reliability, maintainability, and capability over the C/D in areas of, for example, range, survivability, flexibility, weight, and expandability.

Acronyms

ALO	Assembly Layout
CALS	Continuous Acquisition and Life-Cycle Support
CITIS	Contractor Integrated Technical Information Service
DT&E	Developmental Test and Evaluation
EMD	Engineering Manufacturing and Development
FCFQ	Flight Control Flying Qualities
ILS	Integrated Logistics Support
IPPD	Integrated Product and Process Development
IMICS	Integrated Management Information Control System
IPT	Integrated Product Team
ITT	Integrated Test Team
LRIP	Low-Rate Initial Production
MDC	McDonnell Douglas Corporation
MOA	Memorandum of Understanding
Mod SDF	Modular Six Degrees of Freedom
NATF	Navy Advanced Tactical Fighter
NAVAIR	Naval Air Systems Command
PMA	Program Management Authority
RCS	Radar Cross-Section
VSA	Variation Simulation Analysis
WBS	Work Breakdown Structure

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