Design and Implementation of the Product Development Design Decomposition (PD^3)

by

César Bocanegra

Bachelor of Science, Engineering and Applied Science, 1995
California Institute of Technology

Submitted to the Department of Mechanical Engineering
In partial fulfillment of the Requirements for the Degree of

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At the
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May 11, 2001

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ABSTRACT

In today's aircraft industry, the product development process is abundant with opportunities for improvement. There are four issues that are key to a successful business when defining/developing a product: 1) the time it takes to develop a new product; 2) the cost to develop the new product; 3) designing/developing a producible product that is defect free and low cost; and 4) how well the product satisfies the customer's requirements. In addition, the product development process must be continuously improved by applying new techniques and concepts that eliminate non-value adding activities.

This thesis will explain the design and implementation of the Product Development Design Decomposition (PD^3) that was elaborated at Northrop-Grumman Corporation (NGC) to provide a roadmap for systematically improving an existing aircraft development process while at the same time achieving the four key objectives mentioned in the previous paragraph. The PD^3 also provides the user with a decomposition to see the relationships and interactions between product design and the manufacturing system.

The PD^3 was developed applying Axiomatic Design [Suh, 1999] and follows the principles of the manufacturing system design decomposition (MSDD), developed at the Massachusetts Institute of Technology by the Production System Design laboratory [Cochran, Arinez, Duda, Linck, 2000]. One of the purposes of the PD^3 is to integrate the product development process with the design of the manufacturing system.

Although the PD^3 was developed specifically for NGC, it may be applied to other industries. Finally, the PD^3 was designed not only to improve an existing development process, but also to aid a corporation with the design of an entirely new one.

Thesis Supervisor: David S. Cochran
Title: Assistant Professor of Mechanical Engineering

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ACKNOWLEDGEMENTS

In December 1997, after being involved in a fatal accident, I was not motivated at all to apply to MIT. My parents, especially my mom, have always motivated me to further my education and I will always be grateful to them. However, at that time, the person who encouraged me to apply to MIT was my then girlfriend: Nely, now my wife.

Being accepted was just one hurdle to becoming a Master student at MIT. I struggled to obtain a faculty mentor and had to defer my entrance for six months. I then received a phone call from Prof. David S. Cochran. He was offering me a Research Assistantship in his lab. Unfortunately, I had accepted a promotion in AT&T Solutions and had verbally committed myself for at least one year.

Prof. Cochran was very understanding of my situation and managed to defer my entrance for 6 more months. It is then fitting that the first person I acknowledge and thank is Prof. Cochran. His pursuit of perfection helped me become a true professional. He provided me with honest feedback throughout my stay and supported me at all times. Most importantly, I thank Prof. Cochran for giving me the opportunity to become a graduate student at MIT.

I also encountered countless number of people that have helped increase my knowledge base. My deepest gratitude goes to all the professors that provided me with new ideas and concepts. I thank my fellow PSD'ers: Carlos, Memo, José, Jochen, Yong-Suk, Jongyoon, Jim, George, Deny, Ania, and Pat for the lively discussions that helped me understand the principles and concepts behind the design of production systems.

Also, my stay in Cambridge was very pleasant and fun thanks to my friends Ariel, Jose, Elena, Karla, Nicté and the three musketeers: Carlos, Memo and Deny. To all of you, thank you for all those nights full of relaxation (I'll leave it at that!).

This thesis could not have been possible without the help of Northrop-Grumman Corporation and its employees of the Joint Strike Fighter program. I would like to specially thank Jack Pierce, Dick Hartley, Craig Miller, Lucky Tesher, Helen Kozycz, George Vardoulakis, Tom Williams, and Paul Marchisoto. Their valuable time spent with me as well as their incredible patience made my internship very rewarding and fun.

There's another corporation that I would like to thank, AT&T. Their support and help has helped me immensely during my stay at MIT. I thank the encouragement from my friends in HISPA, my co-workers from AT&T Solutions and all my friends at Alestra. Special thanks go out to John Guerra, Jorge Escalona, Marie Santana, Tom Thayer, Ron Tonge, Lynn Brown, Peggy and Brian Tierney, and R.L. Poston.

Last, but definitely not least, I would like to thank God and my family. I believe God has always been watching my back and has giving me this great opportunity to do well in life. My family and their unconditional support have been superb. Tony, Angie, John, Lily and Fredy, you know I love you all! Thank you! Mom and Dad, gracias por su apoyo y por creer en mi siempre. Nely, the love of my life, thank you for being there at all times, for all your help, without you, I couldn't have finished this challenge.

To Nely and toda Mi Familia,

César Bocanegra
May 2001

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

PART I – INTRODUCTION AND CURRENT SITUATION

CHAPTER 1 – INTRODUCTION

A product that meets customer's requirements by solving an existing problem or by making their lives more enjoyable and/or efficient, while at the same time being profitable, is considered a successful product. One of the critical steps of making a successful product is the development process. This thesis will focus on understanding the development process in the aircraft industry and designing a decomposition that will aid in the development of a successful aircraft product.

In today's aircraft industry, the product development process is abundant with opportunities for improvement. There are four issues that are key to a successful business when defining/developing a product: 1) the time it takes to develop a new product; 2) the cost to develop the new product; 3) designing/developing a producible product that is defect free and low cost; and 4) how well the product satisfies the customer's requirements. In addition, the product development process must be continuously improved by applying new techniques and concepts that eliminate non-value adding activities.

This thesis will explain the design and implementation of the product development design decomposition (PD^3) that was elaborated at Northrop-Grumman Corporation (NGC), the Production System Design (PSD) Lab and the Lean Aerospace Initiative (LAI) at MIT. The PD^3 provides a roadmap for systematically improving an existing aircraft development process while at the same time achieving the four key objectives mentioned in the previous paragraph. The PD^3 also provides the user with a decomposition to see the relationships and interactions between product design and the manufacturing system.

Although product development has been defined as "the set of activities beginning with the perception of a market opportunity and ending in the production, sale, and delivery of a product" [Ulrich, K, 1995]; this thesis, will focus mainly on the design phase of the product and the interactions with the manufacturing system.

The PD^3 was developed applying Axiomatic Design [Suh, 1999] and follows the principles of the manufacturing system design decomposition (MSDD) [Cochran, Arinez, Duda, Linck, 2000]. One of the purposes of the PD^3 is to integrate the product development process with the design of the manufacturing system. Also, the PD^3 was developed specifically for NGC; however, it can be used for any product(s) by simply utilizing the appropriate verbiage. One of the main resources used for developing the PD^3 were the Willoughby templates. W.J. Willoughby, Jr., who was at the time Chairman of the Defense Science Board, wrote the Willoughby templates in 1982 and 1985. The focus of these templates is to provide contractors with guidelines to improve their operations from product development to production. To achieve further improvement in the day-to-day operations, Willoughby mentions that a fundamental principle must be used: disciplined engineering. [Willoughby, W.J., 1985]

Finally, the PD^3 was designed not only to improve an existing development process, but also to aid a corporation with the design of an entirely new one.

1.1 Motivation

Although there are countless tools (value stream mapping, process flows, system dynamics tools, design structure matrix 'DSM', Gantt charts, etc.), that help upper management in an engineering company to manage projects during the design phase, none of them have been able to aid in achieving ALL of the four high-level objectives of producing a successful product. The opportunity of developing the PD^3 arose when MIT professor David S. Cochran presented the MSDD to NGC and it was agreed that extending the MSDD to the product development/design phase would be of great value. The motivation for NGC was to apply this new decomposition to all future programs throughout the company but to start with the Joint Strike Fighter program (see Chapter 3).

In a sense, the motivation of this project arose from having products that were not meeting end user's requirements, were not easily producible and/or maintainable, were taking too long to get to the end user and were not being profitable. The product development design decomposition (PD^3) is a decomposition that addresses these objectives or functional requirements (FRs) and at the same time is modifiable to include new concepts and remove obsolete ones.

All this translates to profitability. It has been estimated that approximately 80% of a product's lifecycle cost, technology, configuration, and performance is committed in the product design phase [Blanchard, Fabrycky, 1998]. NGC is attempting to standardize its product design phase in order to minimize the aircrafts lifecycle cost, and at the same time meet all of the customer requirements.

1.2 Goal And Scope Of Thesis

The goal of this thesis is two-fold. First, understand the current development process of NGC and other similar corporations noting the manner in which the four high-level objectives of designing a successful product are undertaken. And second, develop the PD^3 in a way that is recognized by the end user as a "world class" decomposition for ensuring that all the functional requirements (FRs) of the product development phase are met and consequently a successful product is developed.

The scope of this thesis includes background information on the aerospace industry and NGC. It also includes a brief description of axiomatic design, the MSDD, and a detailed explanation of the PD^3 and its applications.

1.3 Approach

Aside from using axiomatic design to develop the PD^3, the scientific method was used to approach this research project. The project began by identifying NGC's need of improving their product development process and assuring there was a clear articulation of the goal in mind: in this case, a decomposition that would help upper management improve their product development process in four respects: meeting customer requirements, producible product, low cost 'profitable' product, and in a timely fashion.

A plan of procedure was then developed to ensure there was a carefully planned mission that helped achieve the research goal. This plan of procedure included the collection of data through interview with current design engineers, upper level management, academia, manufacturing engineers, etc. Also, the plan included the implementation of the resulting decomposition.

Once the plan was devised, the overall problem was divided into more manageable sub-problems. First, the problem was divided into the development of the decomposition, the cost vs. benefit analysis and the implementation of the decomposition. Each sub-problem was then divided even further to smaller, more manageable problems. These sub-problems were then resolved through collection and interpretation of data, and by accepting certain critical assumptions.

Finally, the collection of data during the implementation is being used to validate the cost vs. benefit analysis and do continuous improvement on the product development process and the decomposition itself.

CHAPTER 2 – BACKGROUND INFORMATION (AEROSPACE INDUSTRY)

The Aerospace Industry is defined by the Encarta Encyclopedia as the "complexity of manufacturing firms that produce vehicles for flight—from balloons, gliders, and airplanes to jumbo jets, guided missiles, and the space shuttle. The industry also encompasses producers of everything from seat belts to jet engines and missile guidance systems. The term aerospace is a contraction of the words aeronautics (the science of flight within Earth's atmosphere) and space flight. It came into use during the 1950s when many companies that had previously specialized in aeronautical products began to manufacture equipment for space flight." [Encarta® Online, 2001]

The origins of the aerospace industry go back to the Wright brothers' historic first flights in a heavier-than-air-machine at Kitty Hawk, North Carolina, on December 17, 1903. For the next 11 years, craft manufacturers were largely responsible for airplane construction. However when World War I started in 1914, the needs of the military drove improvement in the aircraft design to the point that in less than two decades, commercial airplanes with high-performance engines and retractable landing gear were being developed and used to carry civilian passengers in the US and in Europe. Further developments in aircraft design and production systems were made during World War II (1939-1945) when the need for military aircrafts was demanded in the tens of thousands. The research that occurred during World War II included the development of the radar, electronic controls, jet aircraft with gas-powered turbine engines, and combat rockets.

2.1 The First Airplane Manufacturers

Demand for airplanes was very small in the early 1900's, however, due to the success of the Wright brothers, Santos-Dumont (Brazilian inventor that designed and flew a biplane in Paris in 1906), and other pioneering aviators, the demand for flying machines on both sides of the Atlantic Ocean grew considerably. These airplanes were built from wood and bamboo frameworks covered with fabric and used modified engines from automobiles and motorcycles or lightweight boat engines to power the planes. Figure 1 shows a picture of the first powered flight that took place on the morning of December 17, 1903 with Orville Wright at the controls.

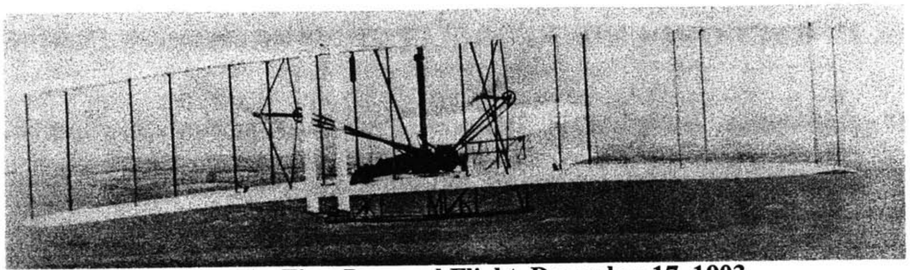

Figure 1 - First Powered Flight, December 17, 1903

2.2 Aerospace Industry During World War I

One of the Wright brothers, Orville, decided that the invention of the airplane would be beneficial to the military and in the years leading up to World War I, spent time demonstrating the invention to officers of the US Army. Soon the European militaries were also viewing demonstrations and making plans to purchase airplanes. In 1909, the French firm Nieuport began producing monoplanes for the French army and for military services in Italy, Britain, Russia, and Sweden. Five years later, during the summer of 1914, Germany, France, Britain, and Russia each had 200 to 300 military planes plus several airships.

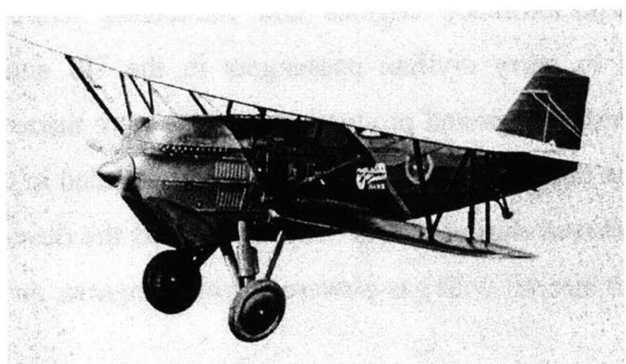

Figure 2 - The Curtiss Hawk Fighter

On the other hand, American manufacturers had only produced 39 airplanes by 1912. As World War I was spreading across Europe in 1915, the US Congress formed the National Advisory Committee for Aeronautics (NACA) to fund research and development in the flight industry. Despite this effort, when the United States entered the war in 1917, it had only 16 airplane-building companies, and only 6 of them had built as many as ten airplanes. The rate of airplane manufacture in Europe and the United States skyrocketed during the war. Britain turned out more than 55,000 airplanes from 1914 to 1918, and Germany produced 40,000 airplanes during the same period. The fledgling

American industry also rallied behind the war effort, turning out 14,000 planes in 1918 alone. By the end of the war, the American aerospace industry had grown to 200,000 workers. [Todd, Simpson, 1986]

2.3 Aerospace Innovation Between The Wars

As in any other defense industry, the pace of airplane production slowed between World War I and World War II. However, improvements in aircraft design, new professional aeronautical engineering schools, and design innovations flourished during this period. Some of the major innovations included the replacement of wooden airframes with lightweight metal structures and the development of engine technology for greater speed and reliability. All these innovations helped the aerospace industry thrive and expand from military use, to civilian and industry use. In 1921, the US Post office started utilizing airplanes for airmail service between San Francisco and New York City. Six years later, in 1927, Boeing developed the Model 40, its first commercial aircraft.

In 1933 Boeing introduced the twin-engine Model 247 airplane, an all-metal, low-wing monoplane with retractable landing gear and room for ten passengers. The Model 247 revolutionized commercial aircraft design but was soon displaced by the larger, faster DC-3 designed and built by the Douglas Aircraft Company. The DC-3 carried 21 passengers and could travel across the country in less than 24 hours, though it had to stop many times for fuel. The DC-3 quickly came to dominate commercial aviation in the late 1930s and helped establish the United States as the leading producer of global airline equipment. [Bilstein, Roger E., 1996]

Figure 3 - First DC-3 to Fly, December 17, 1935

2.4 Aerospace Industry During World War II

When World War II started in Europe, the British and French began placing plane and equipment orders to American manufacturers because their facilities were not being able to handle such a demand for military aircraft. The American aeronautics industry expanded its production capabilities and by the time the US entered the war in December 1941, the nation's aerospace industry was prepared to meet the increased demand for aircraft and produced more than 300,000 aircraft before the war was over.

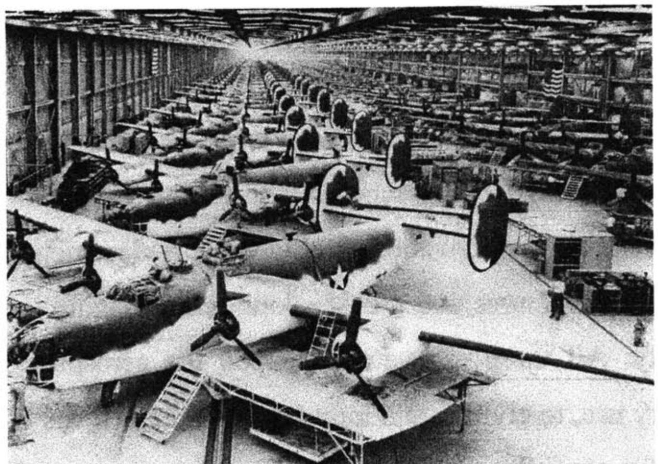

Figure 4 - Production Line for the B-24 Liberator Heavy Bomber (US)

During this war there were also some remarkable innovations in the aerospace industry. The most noticeable innovation was the jet powered fighter plane that resulted from the invention of jet propulsion. Also, pressurized cabins enabled the transport of troops at higher altitudes, above turbulent weather.

2.5 Aerospace Industry During The Cold War

The Cold War was a long struggle that followed World War II between the United States and the Union of Soviet Socialist Republics (USSR). Each country tried to be ahead of the other in military technology and therefore, the defense budgets of both countries grew considerably during this period. Assisted by NACA research and generous federal funding for aeronautical research and development, American firms such as General Electric and Pratt & Whitney developed powerful jet engines. The North American F-86 Sabre fighter and the Boeing B-47 Stratojet bomber were both powered by these jet engines. American manufacturers reaped additional profits during the Cold War by selling helicopters, fighters, and transport aircraft to friendly foreign powers.

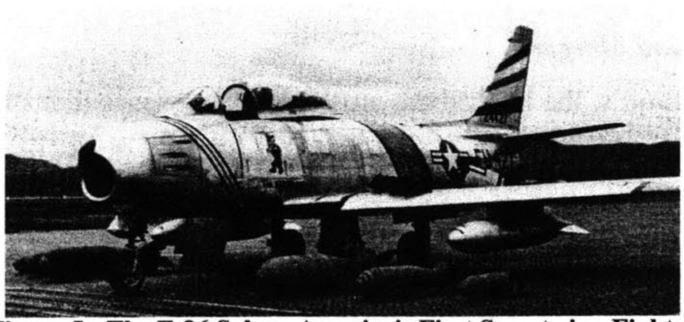

Figure 5 - The F-86 Sabre, America's First Sweptwing Fighter

2.6 Rise of Commercial Air Travel

In 1952, the British de Havilland Comet, was inaugurated as the first commercial airplane powered by jet engines. However, some unforeseen structural weaknesses in the Comet caused a series of crashes, two of them fatal. The Comet was grounded for investigation for several years, giving American manufacturers the opportunity to catch up to their British counterparts. In the late 1950s Boeing and Douglas introduced the jet-powered 707 and DC-8. Pan American World Airways inaugurated Boeing 707 jet service in October 1958, and air travel changed dramatically almost overnight. Transatlantic jet service enabled travelers to fly from New York City to London, England, in less than eight hours, half the time a propeller airplane took to fly that distance. Boeing's 707 carried 112 passengers at high speed and quickly completed the displacement of ocean liners and railroads as the principal form of long-distance transportation. [Encarta® Online, 2001]

In 1970 Boeing introduced the extremely successful 747, a huge, wide-body airliner. The giant aircraft, nicknamed the "jumbo jet," could carry more than 400 people and several hundred tons of cargo. Douglas and Lockheed soon turned out their own versions of the jumbo jet, the DC-10 and the L-1011.

Figure 6 - Boeing's Jumbo-Jet 747 (top) and 707 (bottom)

2.7 Globalization and Mergers

In the late 1960's, the US had the most robust aerospace industry in the world and Europeans were seeking alternatives to reduce their dependency on American manufacturers. The response from the Europeans came in 1967 in the form of the Concorde supersonic transport, the first commercial jet to fly faster than the speed of sound. Three years later in 1970, an alliance of British, French, German and Spanish aerospace companies formed Airbus Industrie. The alliance became a success and in the early 1990's, their Airbus A-300 airplane ranked second only to Boeing in worldwide sales.

The 1990's also saw many mergers in American soil. Martin-Marietta acquired the aerospace division from General Electric Company in 1992, and then merged with the aerospace giant Lockheed two years later. In 1997 Boeing acquired longtime rival McDonnell Douglas. Several European firms announced their intention to combine forces to challenge the newly formed American aerospace giants. In 2000 Boeing announced its intention to acquire Hughes Space Company, the world's leading manufacturer of communications satellites.

2.8 The Wave-Cycle Model

As can be seen in Figure 7, it is clear that aircraft production is dependent on military demand. The two largest spikes in production represent the demand of military aircraft during World War I and II. The top line in the graph shows the different stages of instability and equilibrium in the aircraft production. During a war, initially there's rearmament instability and then there's wartime equilibrium; however as the war is closing to an end, there's demobilization instability, until peacetime equilibrium is reached.

The smaller two spikes are from the Korean-USA war (1955) and the Vietnam War (1967). Finally, towards the end of the graph there's a growing trend due to the fact of the escalating Cold War. If this is continued until the year 2000, there would be another spike in the early 90's due to the Gulf War.

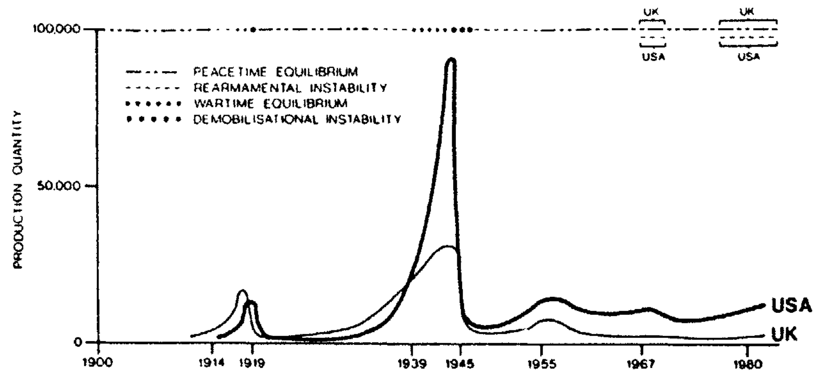

Figure 7 - Aircraft Production and the Wave Cycle [Todd, Simpson, 1986]

The remaining chapters of Part I will focus on the Joint Strike Fighter currently being developed, the F/A-18 E/F Super Hornet product development process and the history of Northrop-Grumman Corporation.

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CHAPTER 3 – JOINT STRIKE FIGHTER

The product development design decomposition (PD^3) described in this thesis (Chapter 7) was originally intended to be included as part of the Joint Strike Fighter (JSF) proposal from the Lockheed-Martin team. In fact, it was developed in 2000-2001 at Northrop-Grumman Corporation, one of the team members of the Lockheed-Martin team. However, due to unforeseen reasons, the Engineering and Manufacturing Development (EMD) phase was postponed at the time of the PD^3 development and it will now be used as a decomposition for other programs. Nevertheless, it is important to mention the JSF program because the PD^3 is based mostly on this initiative.

3.1 History of the Joint Strike Fighter (JSF)

The JSF program began in the early 1990s when several tactical aircraft and technology initiatives of the Department of Defense (DoD) were going through a restructure and integration process. The similar requirements of the Services and US Allies made it feasible to devise a goal of using the latest technology in a common family of aircraft. Also, in 1993, the DoD was considering canceling the Navy's Advanced Attack/Fighter (A/F-X).

A Joint Attack Fighter (JAF) was suggested to replace the Navy's A/F-X program. The main purpose of the JAF was to have a common airframe suitable to the three Services and hence it would have huge cost savings in the product development, manufacturing, and operational phases. Based on these premises, the Joint Advanced Strike Technology (JAST) Program was initiated in late 1993. Along with the program, there were other decisions that the DoD made, such as to continue both the F-22 and the F/A-18 E/F programs, cancel the multi-role fighter and the A/F-X programs, and curtail the F-16 and the F/A-18 C/D procurement.

After the establishment of the JAST program in January 1994, the team members were charged with various initiatives, including the product definition of the new family of common aircraft that will replace several aging aircraft of both the US and the UK. After several concept exploration (CE) studies, the team decided that the most affordable solution would be a single basic airframe design with three distinct variants. One of the objectives of having three variants is to tailor to the mission needs of the military branches to maximize commonality and individual service utility and for export to other allied nations.

3.2 Three Variants of the Joint Strike Fighter

The US Air Force (USAF) would complement its F-22 Raptor with 1,763 conventional take-off and landing (CTOL) fighters. The focus on the CTOL is affordability, flexibility and adaptability for future growth. The CTOL is designed to meet or exceed the performance of the F-16; however, it also offers greater range, stealth, enhanced lethality and lower operating/support costs. The US Marine Corps (USMC) would replace both the AV-8B Harrier and the F/A-18 C/D Hornet with 609 short take-off/vertical landing (STOVL) fighters. Finally, the US Navy (USN) would complement its F/A-18 E/F Super Hornet with 480 carrier variant (CV) fighters. See Figure 8 for the Lockheed-Martin teams' variants of the JSF. The UK had agreed to purchase 150 STOVL fighters. In total, the estimated production of JSF aircraft is 3,002.

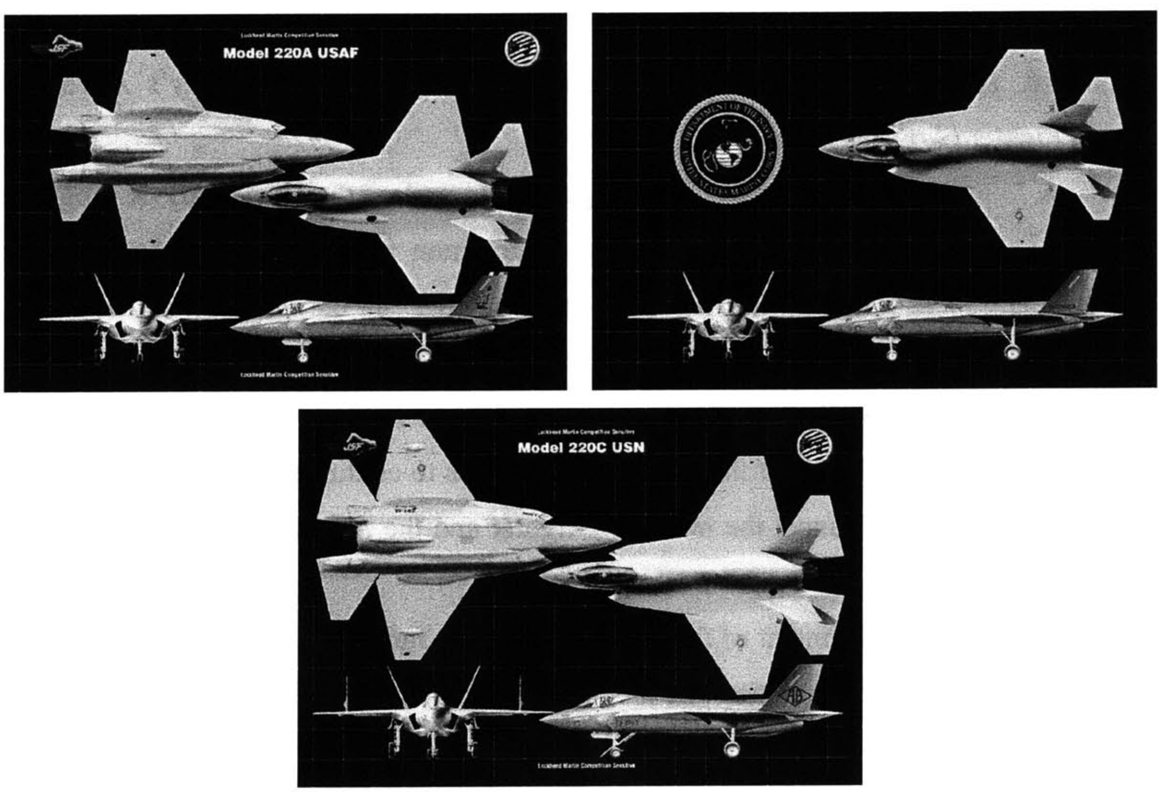

Figure 8 - Three Variants of Joint Strike Fighter, from top left to right: USAF CTOL, USMC STOVL, and USN CV.

In December of 1994, there were four different teams (Boeing, Lockheed Martin, McDonnell Douglas, and Northrop Grumman) that were awarded 15-month contracts for concept definition and design research of the Joint Strike Fighter. Although the teams selected derivatives of the Pratt & Whitney (P&W) F119 engine to power their aircraft, the General Electric (GE) YF120 was identified as the "best fit" for a tri-service solution. In late 1995 the name had been changed from JAST to JSF and on November 15, 1996, the Secretary of Defense had awarded Boeing and Lockheed Martin the Concept Demonstration Phase (CDP) prime contracts.

As mentioned in the previous chapter, Boeing acquired McDonnell Douglas in 1997. On the other hand, Lockheed Martin agreed to have Northrop-Grumman as a sub-prime contractor for the JSF program and included BAE Systems as another sub-prime contractor.

3.3 JSF Current Situation

Currently both teams are preparing to submit proposals for the Engineering and Manufacturing Development (EMD) phase. As mentioned above, the PD^3 is expected to become part of the Lockheed Martin teams' proposal as a decomposition developed by the Production System Design (PSD) Laboratory at MIT, headed by Prof. David S. Cochran, and Northrop-Grumman Corporation in order to help identify and eliminate non-value adding sources of cost to the product development process.

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CHAPTER 4 – NORTHROP-GRUMMAN CORPORATION

The previous chapter mentioned that the Lockheed-Martin team is composed of three main players: Lockheed Martin, Northrop-Grumman, and BAE Systems. This chapter will focus on the history of Northrop-Grumman and their current product development process at their Air Combat System (ACS) business area. This chapter is meant to give the reader a flavor of where a great part of the research took place.

More specifically, this thesis is based on research performed at the ACS business area at Northrop Grumman Corporation (NGC) located in El Segundo, California. This business area is also in charge of the assembly of the F/A-18 E/F Super Hornet. In fact, this thesis required a product development baseline and the Super Hornet product development process was used as the baseline.

4.1 Profile of NGC

Northrop-Grumman Corporation (NGC) has many products and services in both the military and commercial markets. Their core competencies are in defense electronics, systems integration, and information technology. NGC participates on many programs as a prime contractor, principal subcontractor, partner, and preferred supplier. They are aligned along three business sectors to achieve operational efficiencies on a significant scale. The three business sectors are: the Integrated Systems Sector (ISS), based in Dallas, Texas; the Electronic Sensors and Systems Sector (ES^3), headquartered in Baltimore, Maryland; and Logicon Inc., based in Herndon, Virginia.

The Integrated Systems Sector (ISS)

This sector is best known for being the prime contractor for the USAF B-2 Spirit stealth bomber and the Joint Surveillance Target Attack Radar System (STARS), which is the most advanced airborne targeting and battle management system in the world. ISS also produces the EA-6B Prowler electronic countermeasures aircraft, and are upgrading the E-2C Hawkeye early-warning aircraft. This sector also plays a principal role in producing the USN F/A-18 Hornet and the Joint Strike Fighter.

The research in this thesis was performed at the El Segundo, CA location of the ISS where the business area of Air Combat Systems (ACS) develops the Hornets and the JSF. At this site, one can see how NGC brings decades of experience in advanced tactical fighter and long-range strike aircraft development and integration, stealth technologies and composite manufacturing capabilities, avionics systems integration, sensors, advanced commercial aircraft manufacturing processes and aircraft carrier suitability.

ACS is responsible for detailed design and integration of the JSF center fuselage and weapon bay door drive system. This work includes the installation design and integration of installed subsystems; development of a substantial portion of mission systems software; ground and flight control system testing; development of software elements for the flight control system for the carrier variant (US Navy JSF); development support in the areas of signature/low observable and support of modeling and simulation activities, including pilot-in-the-loop simulation, which are necessary from the point of view of the end-user: the pilot.

The Electronic Sensors and Systems Sector (ES^3)

ES^3 has a wide range of products including defense electronics and systems, precision weapons, space systems, marine systems, management systems, and automation and information systems. A significant portion of ES^3 products is radar, including the fire control radar for the F-16, the F-22, and the Longbow Apache helicopter. They are considered world leaders in airspace management, having developed more than 460 civilian air traffic control systems in 12 countries.

Logicon Inc., a Northrop Grumman Company

Among the services that Logicon provides to the federal government is the ANSWER and Millennia programs with the General Services Administration. This NGC subsidiary is also a team member working with the IRS to modernize the nation's tax system. Logicon has expertise in the following information systems: command, communications, intelligence, control, surveillance and reconnaissance. They provide mission planning for the USN, the USAF, and Special Operations Command. Also, they provide base operations support for NASA's Kennedy Space Center, the Cape Canaveral Air Station and Patrick Air Force Base, among others.

4.2 Super Hornet (F/A – 18 E/F) Product Development Process

As mentioned above, the Super Hornet product development process was used as a baseline for both this thesis and the Joint Strike Fighter. The Super Hornet was developed in the Integrated Systems Sector, and more specifically in the Air Combat Systems business area. As new programs become a reality at NGC, some of the knowledge learned from previous programs is used. In this case, the first proposal that was sent to the government was based almost entirely on the current product development process of the Super Hornet. As with any other military aircraft development, the area of research and development constitutes one of the largest expenditures. The development of the entire flight vehicle might take a decade or more and involve thousands of people. The budget for such projects can be easily in the billions of dollars. Therefore, due to the high cost of developing new flight vehicles from the beginning, most large aerospace companies (including NGC) will devote their research and development resources to improving existing products. For example, the engineers may redesign aircraft components to make them lighter and more fuel efficient, or redesign wings or body surfaces to make the craft travel faster.

The Super Hornet vehicle was designed by a workforce organized in a matrix form. In other words, there are different integrated product teams (IPTs) for every detail part and/or component. Every IPT has a design engineer, stress analyst, and a manufacturing engineer as their core members. The IPT also shares many other engineers with other IPTs, such as a sub-systems engineer, a mechanical systems engineer, a methods and procedures engineer, a thermal engineer, etc. Even though an engineer can be appointed to an IPT, he/she is still part of his/her functional group. Therefore, in this type of organization, there is an inherent competition and conflict between the functional group heads and the different IPT heads for the availability of employees, especially for the best-performing individuals. In some cases, when an employee who performs very well, the IPT leader is reluctant to have the employee involved in another project with another IPT because of the high-risk of losing that employee. A solution to these types of problems caused by matrix organizations is discussed in Chapter 7.

Most of the product development process for the Super Hornet, as is with any other complex product in the aerospace industry, took place on fast computers with computer-aided design (CAD) software that allows the engineers to test and modify thousands of design parameters in a relatively short period of time. In fact, the designer can simulate flight in various atmospheric conditions utilizing the CAD software. These parameters mostly deal with the shape and size of the airframe; however, the design engineers also consider thousands of details, such as weight, the placement of the engine(s), design of the cockpit, fuel storage, flaps, wings, weapons bay, landing bay, etc.

Product design is an integral part of product development. The following paragraphs will describe an average process for the product design of a component or sub-system of the Super Hornet developed at Northrop-Grumman. Most of the data contained in this section was obtained through interviews with designers at Northrop-Grumman and collected during a one-week educational lean event, carried out by a small group of NGC employees. [Kozycz, Helen, 2000]

This information was used to develop a more efficient and streamlined product development process to be used for the JSF program. Two different types of tasks were identified during the collection of data: value adding tasks and non-value adding tasks. Value-adding tasks are defined as those tasks that affect the final product's shape, form or function and the end user is willing to pay for them. Non-value adding tasks do not affect the product's shape, form or function and can be divided into two groups: required waste and waiting time. Required waste occurs due to various reasons, including the way the product development process is set-up, non-standard tools, lack of training, rework, reviews, etc. Finally, the waiting time occurs due to non-streamlined processes and/or lack of resources. An example of a process that was studied and analyzed to obtain the times spent on value-adding tasks vs. non value-adding tasks was the product design of a detail part for the Super Hornet. The following figure shows a simplified process flow of what the design engineer does during the product design of a detail part for the Super Hornet.

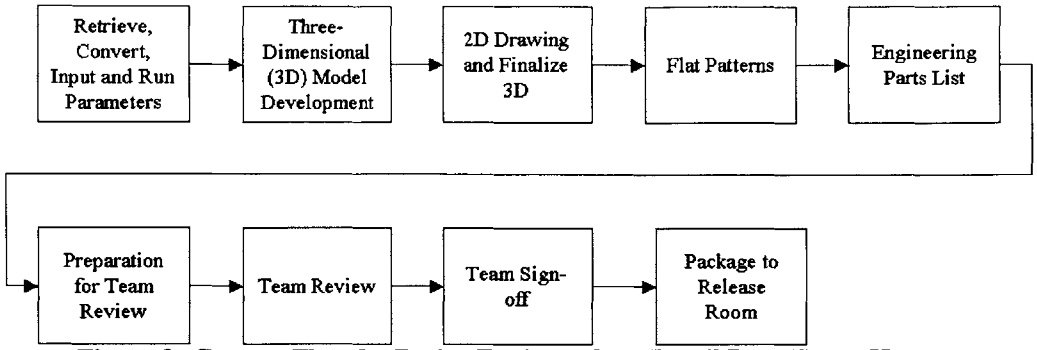

Figure 9 - Process Flow for Design Engineer for a Detail Part (Super Hornet)

A design engineer for a detailed part of the Super Hornet had to retrieve, convert, input, and run all parameters that were given to him by the design concepts or assembly layout. The reason the data had to be converted and inputted into the CAD software was because the parameters were received in a different format. This task usually took the designer approximately 148 hours, of which 28 were considered required waste and the rest are hours waiting for the information. Once the data is converted, the design engineer started the three-dimensional (3D) model development. This task took the longest time of the design process, for a single component, the 3D model development took the design engineer an average of 423 hours, of which only 143 are value added time, 80 hours are waiting time to obtain approval from various engineers such as the stress analyst, manufacturing engineer, etc., and the remaining 200 hours are considered required waste.

At the same time that the 3D model is being finalized, the design engineer begins to develop the two-dimensional (2D) drawings. The 2D drawings are required for the manufacturing group to be able to produce the detail part since they were not trained to utilize CAD software, or if it's a 'buy' part instead of a 'make' part, then the contractor most likely will not have the same CAD software as NGC. For this process step, the design engineer spends a total of 241 hours of which only 163 are value added, 69 are required waste and the remaining 9 hours are waiting time.

The next step in the design process is the development of the flat patterns. The flat patterns are a necessary step in the design process of a detail part because it gives the manufacturing engineers a sense of what the part would look like if it were flat. In other words, if there's a part that should have a shape of an open-ended cylinder (no top and bottom), then the flat pattern would simply be a rectangle (an unfolded cylinder). The problem with this is that currently the design engineer is doing the flat patterns and in many cases, the manufacturing engineering has to re-do them. In fact, one of the manufacturing engineers said during an interview, "The designers should design the part, and give us the [2D] drawings, we will figure out how to make the part." Apparently, the flat patterns done by the designers are often incorrect. However, the flat patterns account for less than 0.5% of the time the design engineer spends on the entire design of the detail part.

Once the flat patterns are completed, the design engineer prepares the engineering parts list. This task doesn't really take too much time out of the entire process, but is a very important task because of its content and need for accuracy. As seen in Table 1 the value added time for this task is on the average 3 hours while the non-value added time is on the average 4.5 hours total. As mentioned previously this task is 1% of the entire design process.

Once the designer has completed the 3D model, the 2D drawing, the flat patterns and the engineering parts list, he/she needs to prepare for the team review, conduct the review and ensure the team signs-off on the design to be later sent to the release room. All these tasks are filled with waiting time, because of the number of people involved. In fact, of the 125 hours (24 + 80 + 21) needed for all these tasks, only 10 hours are value added, 84 hours are waiting and the remainder of the time, 31 hours, are required waste in the form of scheduling meetings, obtaining the room, receive meeting confirmations, etc.

F/A - 18 E/F Baseline Data				
	Task Time (Hours)			
Operation Name	Value Added	Required Waste	Wait	Total
Retrieve, Convert, Input and Run Parameters	0	28	120	148
Three-Dimensional (3D) Model Development	143	200	80	423
Two-Dimensional (2D) Drawing and Finalize 3D	163	69	9	241
Flat Patterns	2	3	0	5
Engineering Parts List	3	1.5	5	9.5
Preparation for Team Review	0	8	16	24
Team Review	10	10	60	80
Team Sign-off	0	13	8	21
Package to Release Room	0	0.5	0	0.5
Totals	321	333	298	952

Table 1 - Design Engineer (Super Hornet) Task Time Observation Table

As can be seen on Table 1, of the 952 hours that it takes a design engineer to produce a product design of a detail part, only 34% of those hours are spent on value added tasks, the remainder 66% of the tasks are considered non-value adding tasks. The PD^3 described in Chapter 7, seeks to reduce the non-value adding tasks, in a way that the time spent on value added tasks are increased to a higher percentage. Some of the actions required to obtain the desired state of a higher percentage of value-adding tasks and activities include:

1. Determine and eliminate any tasks that are not required,
2. Establish concurrent workflow when possible,
3. Improve information workflow, and
4. Define the detail part completely before the detail design begins.

Once the design engineer completes the detail design and the team agrees on the designs, engineers begin building a scale model of the aircraft and subject it to a series of tests. The tests are designed to obtain different data of the aircraft performance and are done with prototype aircraft or by testing the part or component. Some of the testing that is done includes, thermal resistance, pressure resistance, endurance, stress resistance, etc. Once a working prototype of the aircraft has been built, the tests are then conducted in wind tunnels that simulate the conditions that the aircraft would encounter if it were in flight. All the results obtained from the testing, allows the engineers to refine their design as necessary.

Once the design has been finalized, engineers build one or more full-size prototypes of the flight vehicle and subject them to additional tests. Engineers confirm that the structure can withstand the thundering vibrations and heat produced by the jet engines. They use machines to bend, twist, and push the aircraft to verify that it can withstand the stresses it will likely encounter during flight. Engineers also confirm that flight instruments will withstand the pressure and sub-zero temperatures of high altitudes. The engines, landing gear, navigational systems, and other aircraft equipment undergo equally rigorous testing. Finally, pilots take a prototype aircraft for a test flight to verify the results of earlier exercises.

The profile of Northrop-Grumman Corporation and the product development process of the Super Hornet served as the home and the baseline, respectively, for the development of the product development design decomposition (PD^3) described in detail in Chapter 7. Also, the understanding of the current processes that Northrop-Grumman utilizes during the development of their aircraft provided a framework to guide the research and focus on the areas for improvement. With this knowledge, the analysis of the system as a whole can be done using axiomatic design and focusing on the objectives and the means to achieving such objectives.

PART II – PROPOSED DECOMPOSITION

CHAPTER 5 – AXIOMATIC DESIGN

As mentioned before, one of the approaches used to develop the product development design decomposition (PD^3) described in Chapter 7, is the axiomatic design methodology [Suh, 1999]. Professor Nam P. Suh from the Massachusetts Institute of Technology (MIT) developed axiomatic design to give a designer a logical, structured, and scientific approach when developing and selecting the best design solutions to achieve a given design functional requirement. Traditionally, design has not been considered a scientific process but rather a skill that is innate to some, and that cannot be developed [Chu, Cochran, 2000]. The steps involved in axiomatic design include the conversion of customer needs into functional requirements (FRs) and the selection of means for achievement or design parameters (DPs).

5.1 Customer, Functional and Physical Domains

The FRs state *what* the objective is, and the DPs describe *how* those objectives will be achieved. According to Suh, design is comprised of four domains, namely the customer domain, the functional domain, the physical domain, and the process domain and a continuous interaction between these is necessary for the end result of the design process to achieve the initial objectives. The development of the manufacturing system design decomposition (MSDD) [Cochran, Arinez, Duda, Linck, 2000] and the PD^3 take into account the first three domains of design. Figure 10 describes graphically how the customer wants, in the form of expectations, specifications, constraints, etc. are converted into design objectives or functional requirements (FRs), and these in turn are mapped to design parameters (DPs) that describe the physical implementation of the objective.

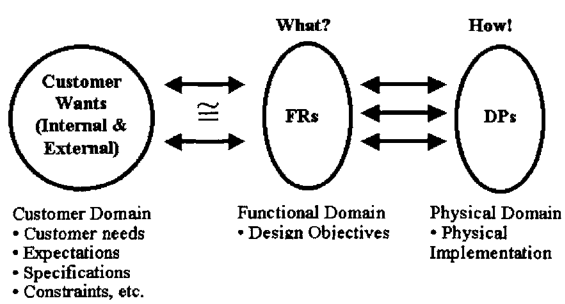

Figure 10 - Three Domains of Design: Customer, Functional, and Physical

The identification of a high-level customer need or objective is the start of the axiomatic design process. Once the customer need at a high-level is identified, for example, a high-level need for a customer could be to become or remain successful and profitable in their business. This need can then be converted into a high-level functional requirement (FR) such as "maximize return on investment." Next a high-level design parameter (DP) should be selected and mapped to the high-level FR.

5.2 Zigzagging Method of Decomposition

The selection and synthesis of DPs is usually a creative process. Also, at high-levels, the DPs may be conceptual and/or abstract to the point where a general solution, system or process is described but without sufficient information to implement the DP. Decomposition of the high-level FR into lower-level FRs is required such that their corresponding DPs are more explicit and contain enough detail for a concept to be implemented. This method is called the zigzagging method of decomposition and can be seen in Figure 11.

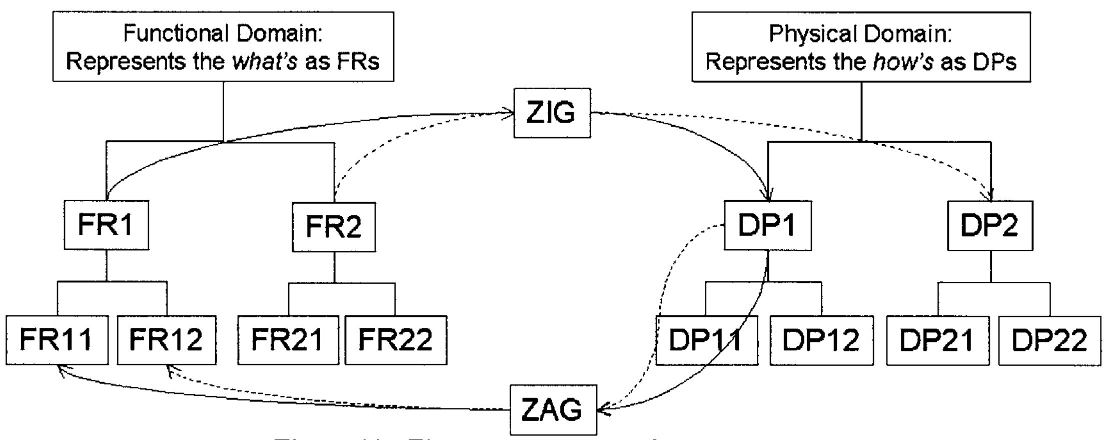

Figure 11 - Zigzagging Method of Decomposition

In theory, the decomposition is not complete until all the FRs and DPs have been decomposed to an operational level of detail.

5.3 Design Matrices and Graphical Representation of FR-DP relationships

One of the major advantages of axiomatic design is the graphical representation of the relationships between FRs and DPs, which are usually shown in the decomposition with a solid line (if the DP affects directly the FR) and with dotted lines (if the DP affects indirectly the FR). These relationships are also shown by means of design matrices or in vector form as in equation (1).

$$\{FRs\} = [A]\{DPs\} \tag{1}$$

The design matrix [A] and its elements indicate the relationship between the DPs and the FRs of the same branch. For example, the following design equation contains a 3X3 matrix with different elements:

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} X & - & - \\ - & X & - \\ X & X & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} \tag{2}$$

The elements (X, -) of the design matrix [A] shown in equation (2), indicate the existence or absence of a relationship between a DP and the associated FR (e.g. A_{11} indicates that DP_1 affects FR_1, where A_{21} indicates that DP_1 does not affect FR_2) [Tate, 1999]. The information contained in equation (2) can also be represented graphically as follows:

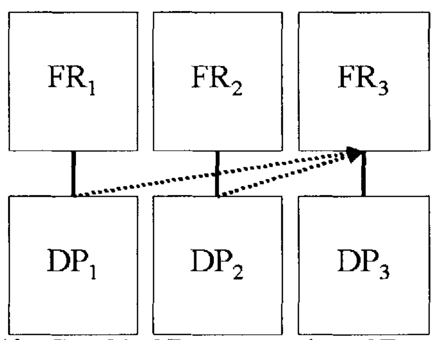

Figure 12 - Graphical Representation of Equation (2)

The PD^3 described in chapter 7 show the relationships between the FRs and DPs with both the design matrices and graphically. To determine whether a certain DP affected an FR the following questions were asked: 1) Does DP_i affect the system performance of FR_j? and 2) Would failing to implement DP_i impede the product development process to satisfy FR_j? By answering these two questions, the entries of the design matrices for the PD^3 were filled accordingly.

5.4 Independence and Information Axioms

Professor Nam P. Suh developed two axioms that need to be satisfied in order to select the best set of possible design parameters (DPs) and therefore develop a good design [Suh, 1999]. The first axiom is referred as the independence axiom and the second axiom is referred as the information axiom.

The *independence axiom* specifies that an acceptable or good design must maintain the independence of all functional requirements as a result of the selection of the DPs. In this case satisfying a particular FR should not affect the feasibility of satisfying another FR. In the best-case scenario, the DP for an FR can be adjusted without affecting other FRs. If this is not the case, then one or all the DPs infringing on the other FRs should be reformulated to eliminate the interdependency. It must be noted that the independence axiom refers to the achievement of functional independence and not of physical independence. In other words, the physical attributes to achieve different FRs of a design can be combined (physical integration) and still achieve separate FRs (functional independence).

The *information axiom* states that the information content of the design must be minimized. This axiom states, that given two un-coupled designs, the design in which the DPs have the highest probability of success in achieving the FRs is preferred and that simpler designs are better and therefore the selection of DPs should take into consideration the effectiveness of the solution. This axiom deals with quantifying the complexity of solutions, which can be very challenging to perform and therefore this axiom is not easily implemented when decomposing a high-level functional requirement.

5.5 Uncoupled, Partially Coupled, and Coupled Designs

The development of the PD^3 takes into consideration both axioms described above; however, functional independence was not easily achieved. When each DP affects **only** its associated FR (i.e. a diagonal matrix), then it is said that there is no coupling or the design is **uncoupled**, and functional independence is attained. When the rows and columns of the design matrix can be interchanged such that the matrix is lower triangular, it is called a **partially coupled** design, and if the DPs are operated in proper sequence, then functional independence is achieved also. When the rows and columns of the design matrix cannot be interchanged to form a lower triangular then the design is said to be **coupled** and functional independence is not achieved. The graphical representation of these three states is shown below:

$$\begin{bmatrix} X & - & - \\ - & X & - \\ - & - & X \end{bmatrix} \quad \begin{bmatrix} X & - & - \\ X & X & - \\ X & X & X \end{bmatrix} \quad \begin{bmatrix} X & - & X \\ - & X & - \\ X & - & X \end{bmatrix}$$

Uncoupled Design | Partially Coupled Design | Coupled Design

Figure 13 - Uncoupled, Partially Coupled, and Coupled Design Matrices

An ideal design would be one with an uncoupled design matrix; however, a design is acceptable if its design matrix is partially coupled. When the design matrix is coupled, the FR-DP pairs need to be revised to achieve functional independence or at least obtain a partially coupled design. When a design is partially coupled, it is also said to be path dependent. In other words, the FR-DP pairs on every level should be arranged in such a way that the pair with the DP that influences the most FRs is located on the left side. Therefore, the implementation of the decomposition should theoretically be done from left to right in order to achieve the desired system-design goals.

The following process flow [Cochran, Arinez, Duda, Linck, 2000] was used when decomposing the high-level functional requirement for the PD^3.

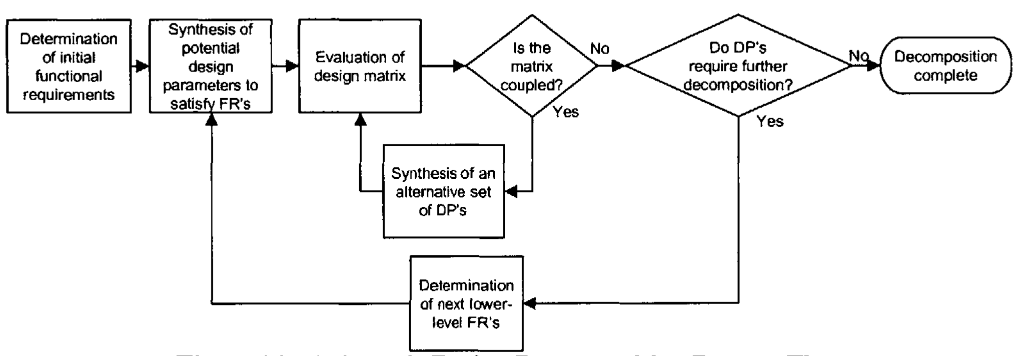

Figure 14 - Axiomatic Design Decomposition Process Flow

Axiomatic design proved to be an excellent methodology to achieve the desired research objectives stated in the introduction of this thesis. Although there exists many other design methodologies, such as Quality Function Deployment (QFD) [Clausing, 1994] and IDEF [Mayer, Crump, Fernandes, Keen, and Painter, 1995], these design methodologies do not show the relationships between the objectives (FRs) and the means to obtaining such objectives (DPs).

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CHAPTER 6 – THE PSD FRAMEWORK AND THE MSDD

The Production System Design (PSD) Laboratory, headed by Prof. David S. Cochran, at the Massachusetts Institute of Technology (MIT) has developed a powerful document, which enables corporations to design their production systems from a holistic, systematic, comprehensive and logical approach, but always aligned to the business' high-level objectives. This document is called the Production System Design (PSD) Framework [Cochran, 1999].

In this thesis, the term "system" is used referring to the set of elements with definite inputs that are acted upon to produce a desired output [Parnaby, 1979]. Also, a distinction must be made between a manufacturing system and a production system. Prof. Cochran makes this distinction as follows:

> "A Manufacturing System consists of the arrangement and operation of machines, tools, material, people and information to produce a value-added physical, informational or service product whose success and cost is characterized by measurable parameters. The Production System consists of all of the elements and functions that support the manufacturing system." [Cochran, 1999].

Based on Prof. Cochran's definition, a manufacturing system encompasses all the elements that are directly involved in the process of adding value to the inputs to yield the products of the system. On the other hand, a production system encompasses the manufacturing system, together with the supporting elements and resources associated with it. The first section of this chapter briefly describes the PSD framework, which includes the Manufacturing System Design Decomposition (MSDD), the MSD Evaluation Tool, System Design Flowchart, and the Deployment Steps. The second section contains a broader description of the MSDD.

6.1 The Production System Design Framework

Traditionally, the design of production systems has been done independently from the business objectives and with the sole intent of optimizing individual sub-systems, which do not necessarily improve the entire system [Cochran, Kim, Kim, 2000]. The resulting production systems are often disconnected; and become difficult to control and manage, and do not meet the enterprise's objectives. Following a systematic, logical, and comprehensive methodology to design a production system has traditionally been practiced by very few enterprises.

As mentioned before, the PSD framework is a document that was recently developed to aid corporations in their design of production systems. This framework applies the axiomatic design methodology described in Chapter 5, to the design of manufacturing systems and one of its more powerful tools is the MSDD described in section 6.2. Along with the MSDD, the PSD framework also identifies the thought process and the key decisions that need to be made during the design of a production system, and it serves as a method to communicate those decisions to the people in an organization. Finally, the PSD framework also contains two useful tools that help the user during the deployment and subsequent control of the manufacturing system. In addition, the PSD framework encapsulates the knowledge from the Toyota Production System literature and experience in such a way that a system designed using the PSD framework will achieve the total success of lean manufacturing.

One of the key advantages of the PSD framework, as opposed to how manufacturing and production systems have been "designed" traditionally, is that it provides the connection between the high-level goals of an organization and the many decisions that must be made to design the sub-systems that are part of the entire system (ex. equipment, control system, material replenishment, etc.) [Cochran, 1999]. Having this clear and well-defined connection between the sub-systems and the high-level goals enables the entire system to achieve these enterprise objectives, which is ultimately the driving force of any manufacturing company. As the objectives of the enterprise change, the manufacturing system also evolves to achieve the desired objectives.

Figure 15 shows a graphical representation of the PSD framework, which is composed of the MSDD (described in the following section), the MSD matrix, the MSD evaluation tool, and the Deployment Flowchart and Steps for Implementation. Further information on the remaining elements of the PSD framework can be found in the literature associated with the PSD framework [Cochran, 1994; Carrus and Cochran, 1998; Suh, Cochran and Lima, 1998; Cochran, 1999]. Also, several examples of the application of the PSD framework to the design of particular production systems can be found in the literature [Arinez et al., 1999; Bröte et al., 1999; Charles, Cochran, Dobbs, 1999; Duda et al., 1999].

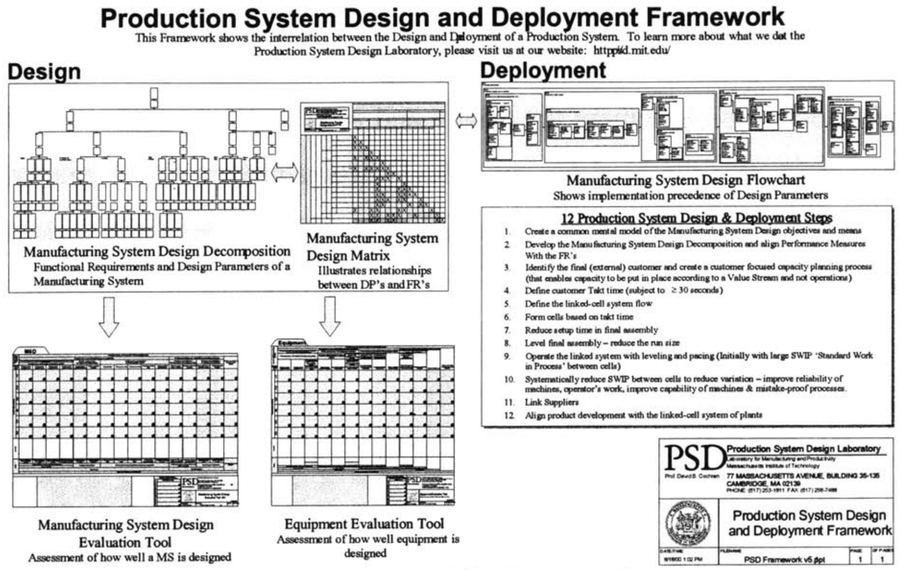

Figure 15 - The PSD Framework

6.2 The Manufacturing System Design Decomposition (MSDD)

The previous section described the PSD framework and mentioned that the Manufacturing System Design Decomposition (MSDD) is one of its components. This section will describe in more detail the MSDD because it is considered very valuable and crucial to improve an existing, or design, a new manufacturing system. The MSDD is based on axiomatic design methodology [Suh, 1999] and it "identifies the design relationships to achieve a 'lean' production system design" [Cochran, 1999]. There are four main objectives of the MSDD as explained in the Journal of Manufacturing Systems [Cochran, Arinez, Duda, Linck, 2000]:

1. Separate objectives from the means of achieving those objectives,
2. Relate low-level activities and decisions to high-level goals and requirements,
3. State the interrelationship among the different elements of a system design, and
4. Provide a common platform to effectively communicate this information.

As mentioned in Chapter 5, design decomposition begins with a high-level objective. In the MSDD case, this objective or functional requirement (FR) is *FR-1: Maximize long-term return on investment (ROI)*. To satisfy this high-level FR, a high-level design parameter (DP) or solution must be assigned: *DP-1: Manufacturing system design*. Per axiomatic design methodology, an FR-DP pair should be decomposed until there's enough detail to implement the design and as can be seen with *DP-1*, there's not enough detail and hence the need for lower-level FRs is presented. A schematic view of the MSDD can be seen in Figure 16. A complete version of the MSDD can be found in appendix A.

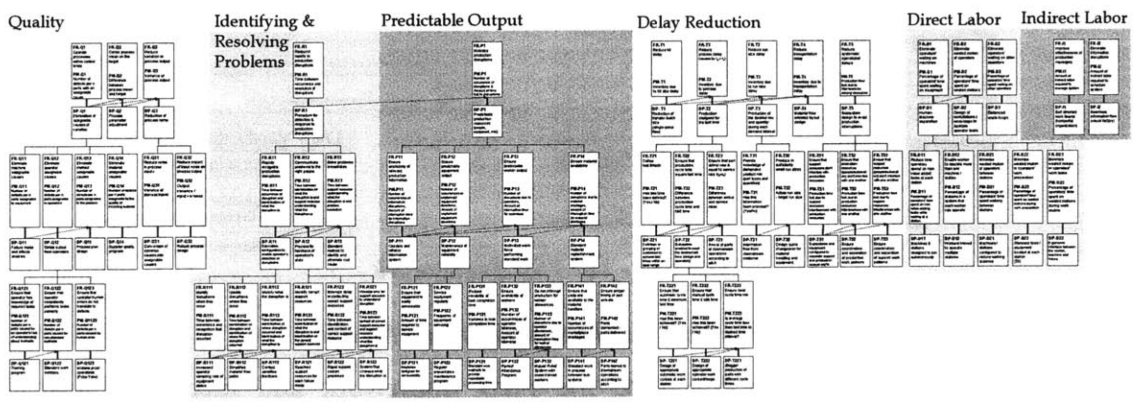

Figure 16 - Schematic View of the MSDD Version 5.1

The highest-level FR, *maximize long-term ROI*, was chosen because it is universally accepted that a system is considered to be performing well when its return on investment is also considered to be above industry average throughout the life cycle of the system. There are various aspects of an enterprise that affects their *ROI*, however, the MSDD was developed with a focus on the impact that the manufacturing system has on *ROI* and hence the DP that corresponds to this high-level FR is *manufacturing system design*. This FR-DP pair was decomposed into lower-level FRs based on the formula to calculate return on investment:

$$ROI = \frac{\text{Revenue - Cost}}{\text{Investment}} \tag{3}$$

The three components that directly affect *ROI* are revenue, cost and investment according to equation (3). Therefore, in order to maximize *ROI*, cost and investment must be minimized while revenues must be maximized. These three objectives became the level II FRs, i.e. *FR-11: Maximize sales revenue*, *FR-12: Minimize manufacturing costs*, and *FR-13: Minimize investment over production system lifecycle*. In order to maximize sales revenues, *DP-11: Production to maximize customer satisfaction* was developed as the means to achieve *FR-11*. The design parameters for *FR-12* and *FR-13* are *DP-12: Elimination of non-value adding sources of cost*, and *DP-13: Investment based on a long-term strategy*, respectively. These FR-DP pairs are part of levels I and II of the MSDD, and can be seen represented graphically in Figure 17.

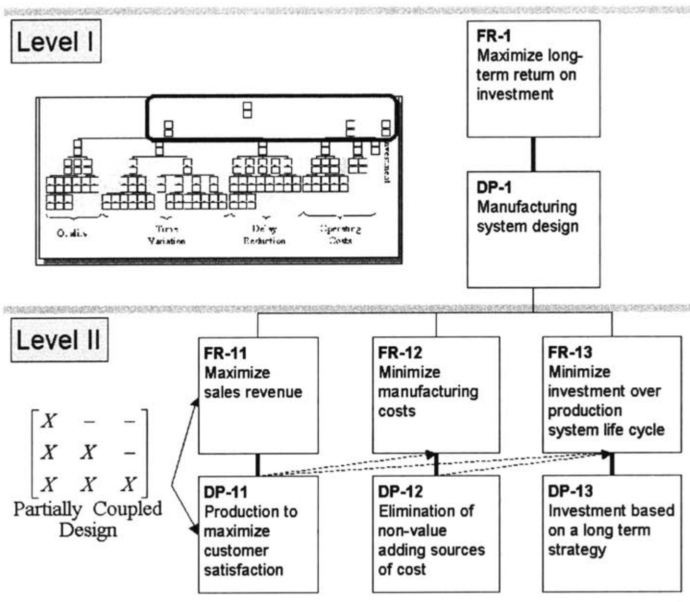

Figure 17 - High Level FR-DP Pairs of the MSDD v5.1

As the FRs are decomposed further, new levels are added and branches can be identified based on their content and intent. The current MSDD, version 5.1, is composed of six levels arranged in six different branches. [Cochran, Arinez, Duda, Linck, 2000] The six levels were obtained by following the axiomatic design process of decomposing the FR-DP pairs into lower-level FRs, while the different branches were obtained directly from the decomposition of Level II FR-DP pairs. The six different branches are: Quality, Identifying and Resolving Problems, Predictable Output, Delay Reduction, Operational Costs, and Investment. For further information regarding the MSDD, please refer to reference [Cochran, Arinez, Duda, Linck, 2000].

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CHAPTER 7 – PRODUCT DEVELOPMENT DESIGN DECOMPOSITION (PD^3)

There are many reasons why there was a motivation for developing the product development design decomposition (PD^3). It is an attempt to provide a standard way to develop products throughout an enterprise. It is also a natural extension to the MSDD described in Chapter 6. And finally, it is a decomposition to reduce cost as a result of eliminating non-value adding and redundant activities. One of the current problems in product development that the PD^3 intends to alleviate is the lack of communication that occurs between a product designer and the manufacturing engineer due to the lack of knowledge transfer between both persons. This lack of communication results in re-work, for example, this condition occurs when the designer does not know what the capabilities of the manufacturing system are and when the manufacturing engineer receives the design, it has to be returned to the designer for re-work.

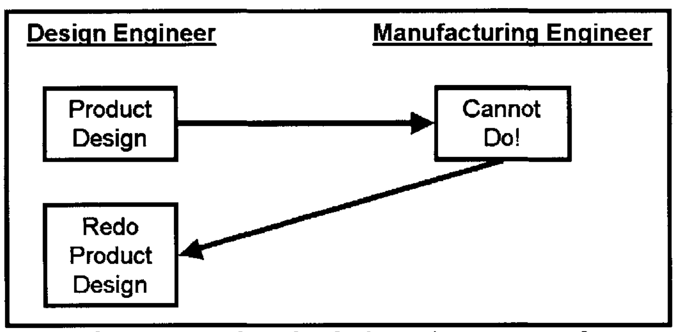


Figure 18 - Process that occurs when the designer is unaware of process capabilities.

The PD^3 also provides the engineering management a decomposition to implement various solutions such as easily accessible process capability databases, collocation of resources, standardization of software tools, and supplier involvement, among others. It also provides a foundation to advance the product development organization design as the technology advances. Finally, it can be used to serve as a roadmap of objectives and solutions to implement.

The product development design decomposition (PD^3) follows the same methodology (axiomatic design [Suh, 1999]) as the Manufacturing System Design Decomposition (MSDD). The main resources used to develop this decomposition were the interviews conducted at Northrop-Grumman Corporation, the Willoughby templates [Willoughby, W.J., 1985], and the research performed by the Production System Design

(PSD) lab, headed by Prof. David S. Cochran, at the Massachusetts Institute of Technology. For a complete version of the PD^3 please refer to appendix B.

At the very top level the functional requirement *FR-01* has as objective to achieve "*A product design and product definition that meets internal and external customer requirements.*" Internal customers are defined as all the stakeholders within the enterprise (manufacturing, finance, marketing, etc.) and the external customer as the end user(s) of the product. The design parameter (DP) of *FR-01* is the PD^3 itself.

The various strengths of axiomatic design discussed in Chapter 5, and namely the emphasis of separating the objectives (FRs) from the means (DPs) and the structured decomposition process, made it particularly well suited to achieve the proposed research objectives. Also, this approach forces the definition of the objectives and the means to achieving the objectives in a structured and **uncoupled** or **partially coupled** manner. This is especially helpful in the product development process where the "product" is a design or data, and not a physical part. Therefore, there are more people-people interactions in the product development phase compared to the interactions during the production phase and these interactions can interrupt the flow of the data or the design when the objective and/or the means are not clear to the people involved.

The FR was chosen because it states that there are two different types of customers, which often have contradicting requirements. For example, the external customer might have a weight requirement of less than *x lbs* for a certain part, but the internal customer's process capability requires a weight requirement greater than *x lbs* for that same part. In order to meet the requirements of all customers, a product design must meet five basic FRs as specified by the next level of the decomposition:

1) Satisfy external customers requirements (*FR-011*),
2) Design a producible product (*FR-012*),
3) Reduce the amount of time it takes to design the product (*FR-013*),
4) Ensure the product will be profitable (*FR-014*), and
5) Ensure there is continuous improvement (*FR-015*).

These five lower-level objectives with their corresponding design parameters can be seen in Figure 19.

The implementation order of the FRs is very important to ensure a successful product. The first FR states that the product design must satisfy the external customer requirements, without meeting this objective, the product design is consider unsuccessful. As a second objective, the product design must be producible utilizing the existing process capability of the assembly/production system or by adapting the current system with new process capability. The third objective has to do with reducing the time it takes to design the product. Although this is an important and crucial objective in today's environment, the latter objectives become less important for the success of the product. The fourth objective has to do with profitability and ensuring that direct and indirect labor costs are optimized. The fifth FR ensures the organization improves its product development process by learning from mistakes and incorporating new and innovative product development concepts to subsequent programs.

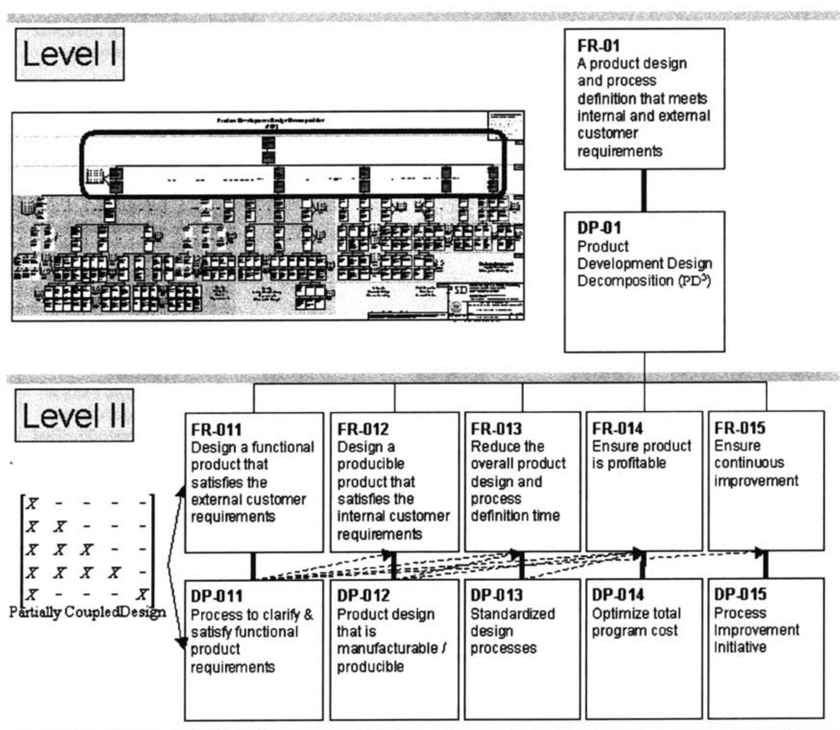


Figure 19 - Top-level FR-DPs of the PD^3

7.1 Quality – Satisfy End User Requirements (FR-011)

As stated above, in order to satisfy external customer requirements (*FR-011*) a DP has been defined as the means to achieving the objective as *DP-011 – Process to clarify and satisfy functional product requirements*. This FR-DP pair is decomposed into the most important branch of the PD³. It is the heart of the product definition phase. It is during this phase of the development of a product that an estimated 85% of a weapon's total life-cycle costs are committed before a weapon system enters full-scale development [Gansler, 1989].By asking the simple question of "how are end user's requirements satisfied?" this branch was developed. Four functional requirements were developed to answer this question: First, there is the need to understand the external customer's requirements (*FR-U1*); second, a product must be designed to satisfy those requirements (*FR-U2*); third, the design has to be validated (*FR-U3*); and finally, the contract obligations must be met (*FR-U4*). The corresponding DPs of these high level FRs are illustrated in Figure 20. Also, the following sub-sections provide a more detailed description of each FR-DP pair and their subsequent decomposition.

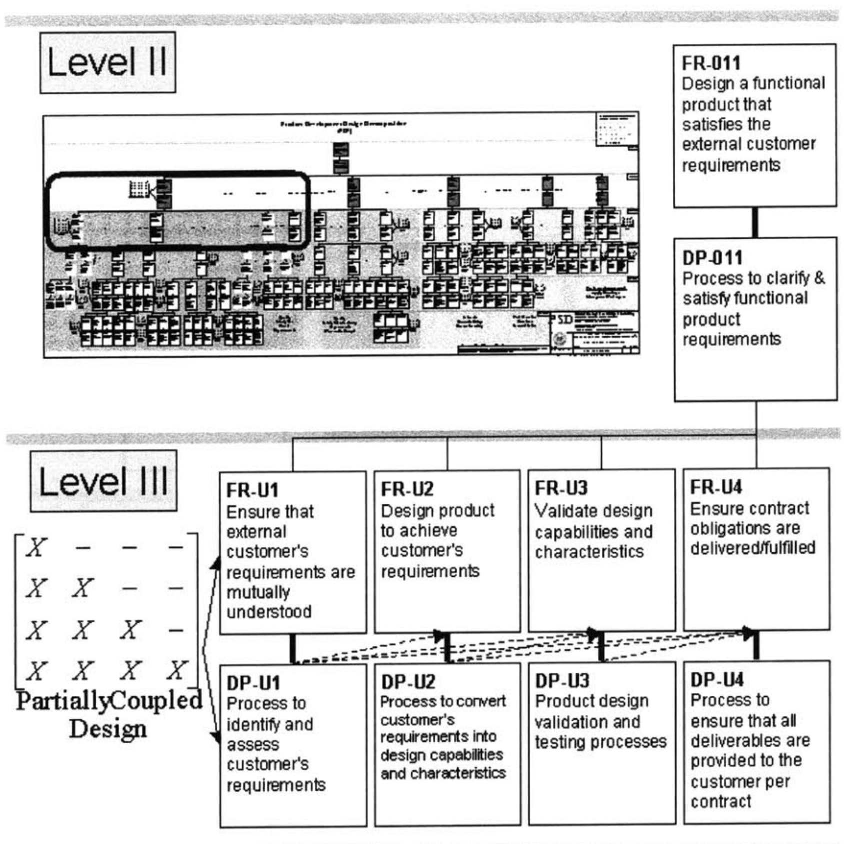


Figure 20 - Quality – Satisfy External Customers

The partially coupled design matrix in Figure 20 depicts the affect that every DP has on its subsequent FR, but not vice-versa. It's a lower-triangular matrix, which is an acceptable, path dependent design in axiomatic design [Suh, 1999] methodology.

7.1.1 Understand your external customer's requirements (FR-U1)

This branch of the PD^3 describes the importance of mutually understanding and agreeing on the external customer's requirements. It is the first objective that needs to be satisfied in order to be able to meet the higher-level functional requirement of satisfying the external customer's requirements. The corresponding *DP-U1 – Process to identify and assess customer's requirements* suggests that the solution to this objective is to first identify the external customer's FRs and then to assess these FRs with the customer in order to reach a mutual agreement. *FR-U1* is decomposed into two FRs: *FR-U11* and *FR-U12*. These FRs and their corresponding DPs are illustrated in Figure 21.

The first FR, *FR-U11*, describes how to avoid risk associated with having a mis-understanding with the baseline requirements. *FR-U11* requires participation from both the external customer and the provider. As a solution, *DP-U11 – Study and understand contract* has been assigned as the means to achieving this FR. Basically, this FR-DP pair needs to be met to ensure that the client and the provider are both in agreement and the baseline requirements of the product are well understood. This FR can be further decomposed into having face-to-face discussions with the client to establish format, scope, and schedule for contract deliverables and also to establish metrics for success criteria.

The second FR, *FR-U12*, recognizes the fact that product requirements change during the product development phase, especially in the aerospace industry where the product development phase can take decades and the technology changes rapidly. Therefore, *FR-U12* identifies the objective of knowing what to do when the customer's requirements change. The means to achieve this objective is summarized as *DP-U12 – Understand "changes clause" in baseline contract.*

Also, the design matrix in Figure 21 shows an un-coupled design, which implies that each design parameter (DP) is directly linked to its own functional requirement but does not affect the other FRs, i.e. functional independence has been achieved. The two DPs are independent of each other because understanding the contract requirements with the external customer is not related to how an enterprise should respond when those requirements change. *DP-U11* specifies open communication with the external customer to reach mutual agreement and *DP-U12* describes the need to develop a process to follow when a change in the external customer requirements occur.

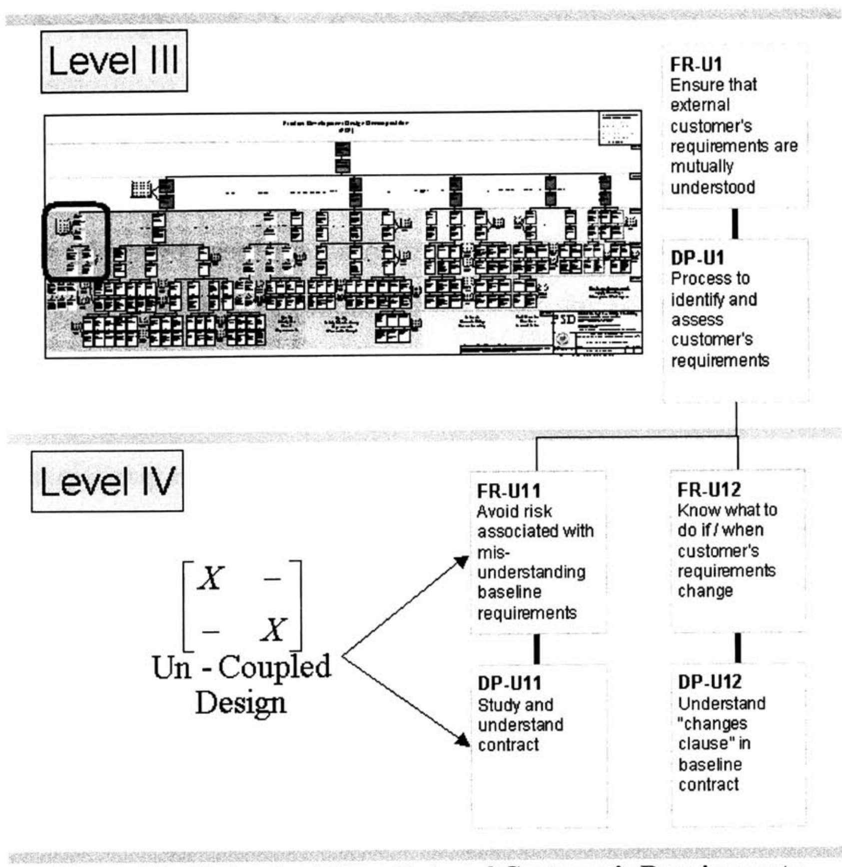


Figure 21 - Understand Your External Customer's Requirements

<u>*7.1.2 Design product to achieve external customer's requirements (FR-U2)*</u>

Once the external customer's requirements have been understood and mutually agreed upon, the designer has to define and design a product that will achieve those requirements. The DP for this FR is *DP-U2 – Process to convert customer's requirements into design capabilities and characteristics*. To achieve this FR-DP pair, three FRs are required and can be seen in Figure 22.

The decomposition branch shown in Figure 22 can be viewed as the core of what a supplier needs to do to allocate tasks to designers, to ensure that resources are available and finally, to design the product itself. The first functional requirement, *FR-U21*, illustrates the need to allocate the different tasks identified in a statement of work to different sub-teams or employees according to their core competencies. For example, one of the tasks that employees at Northrop-Grumman need to do before design is started is to identify the key characteristics of the product. A key characteristic (KC) is a product, sub-assembly, part, or process feature that significantly impacts the final cost, performance, or safety of the product when the KC varies from nominal [Thornton, 1997]. In this case, the right people have to be selected to identify the KCs. The KCs are then aligned with the customer requirements in such a way that the designer knows what customer requirements are at risk if a certain KC is not met. Finally, the designer identifies the parameters to use in the design and manufacturing requirements to measure the results.

The product design of the detail part is a critical phase in the development process. It requires the planning and design of an achievable workload to avoid missed deadlines. A time-phased statement of work is required so that realistic milestones and deliverables are established for a successful completion of the product design.

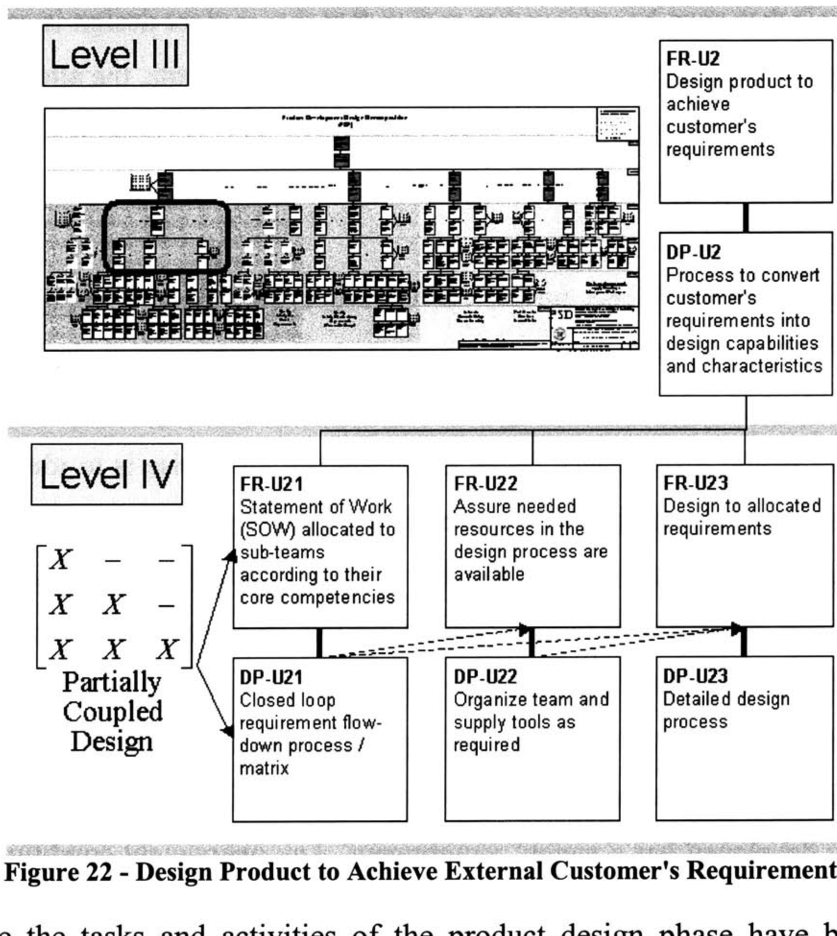


Figure 22 - Design Product to Achieve External Customer's Requirements

Once the tasks and activities of the product design phase have been defined, assigned and time-phased, a program manager is responsible for assuring that the required resources are available. This lower-level objective is depicted as *FR-U22* and is described below.

The second lower-level FR, *FR-U22: Assure needed resources in the design process are available*, is an FR for designing a successful product because it ensures that the necessary resources are available. In this case, there are three types of resources that need to be allocated: 1) a capable organization structure (i.e. management, leaders, and support mechanism); 2) teams (i.e. experienced workers and new hires); and 3) capable tools and processes. To achieve *FR-U22*, the enterprise must organize sub-teams or integrated product teams based on the statement of work with capable leadership and team members. In addition, the teams require standard and capable tools that will help the team achieve the workload in the statement of work.

The third lower-level functional requirement in Figure 22, *FR-U23: Design to allocated requirements*, has as a design parameter *DP-U23: Detailed design process*. It is this FR-DP pair that must be achieved to ensure that the product design is complete. The design engineer has already understood the customer requirements, the allocation of tasks with milestones and deliverables has been performed, and the required resources have been made available to the capable teams. This FR specifies that is now time to perform the product design.

Although *FR-U23* is not further decomposed, the following paragraphs describe briefly the FR-DP pairs that must be achieved during the product design phase of a military aircraft. The materials of a fighter aircraft comprise the greatest amount of costs. Therefore, one of the main objectives of the aerospace enterprise is to identify, develop and validate materials by designing the aircraft for optimal performance with low costs in material. The enterprise can achieve this FR by performing research on new materials, trade studies and development testing and having this research available to its designers in a capable, easily accessible database.

An objective that is tied with the type of materials to use when developing a military aircraft is the prevention of an overweight condition. In this case, the fighter aircraft being developed has a weight requirement. Any overweight condition can hinder the performance of the aircraft in many respects. The DP to achieve this objective is to design the product development process so that it will automatically detect any overweight condition and make the necessary corrections.

A greater cost of the aircraft, than the material itself, can occur for the end user in terms of supportability (i.e. maintenance). This additional cost is tied to the high-level objective of customer satisfaction. Therefore, a designer should take into consideration the FR of minimizing maintenance costs during the design phase (this FR-DP is a lower-level FR of *FR-U23*). The external customer will be more satisfied if the maintenance costs of the product are minimal, given that all the other FRs have been fully satisfied. Unfortunately, in the aerospace industry, maintenance of aircraft is considered one of the largest costs for the end user and hence the developer needs to consider the operational requirements during the products lifecycle to minimize maintenance costs. A DP for this lower-level functional requirement is the utilization of material that operates well below maximum allowable capability and the involvement of maintenance engineers during the design phase to make the product easily serviceable based on the customer's maintenance plans.

Finally, the enterprise must ensure that all tasks of the product design process are completed and documented in a format that can be easily understood by the customer. This objective is achieved by monitoring the design processes and the milestones and metrics that were established at the beginning of the design phase. The output of the design phase should also be organized in a standard format (i.e. product definition package) and in a manner that satisfies the requirements of the customer.

Again, the design matrix for the decomposition in Figure 22 is a partially coupled design, which is a path-dependent design. The structure of the decomposition depicts the DPs affecting their subsequent FRs and path dependency is established with this design from left to right.

7.1.3 Validate design capabilities and characteristics (FR-U3)

Before turning the product design to the manufacturing department for full production, the integrated product team (IPT) is responsible for validating the design capabilities and characteristics of the product. This validation becomes the third objective of four to ensure the design satisfies the external customer requirements and is shown as *FR-U3: Design capabilities and characteristics validated.* The DP to achieve this objective is defined as *DP-U3: Product design validation and testing processes.* See Figure 23, for this FR-DP pair and its subsequent decomposition.

There are basically three objectives that need to be achieved in order to fully meet *FR-U3*. First, the design data used for the product needs to be validated (*FR-U31*). Second, the parts and/or sub-assemblies that comprise the product also need to be validated (*FR-U32*). Finally, because there are many requirements from both the end user and government entities (such as the Federal Aviation Administration (FAA)), the validation data must be compiled and prepared into a final report (*FR-U33*). The corresponding design parameters or solutions to these three functional requirements are *DP-U31*, *DP-U32*, and *DP-U33*, respectively and are depicted in Figure 23.

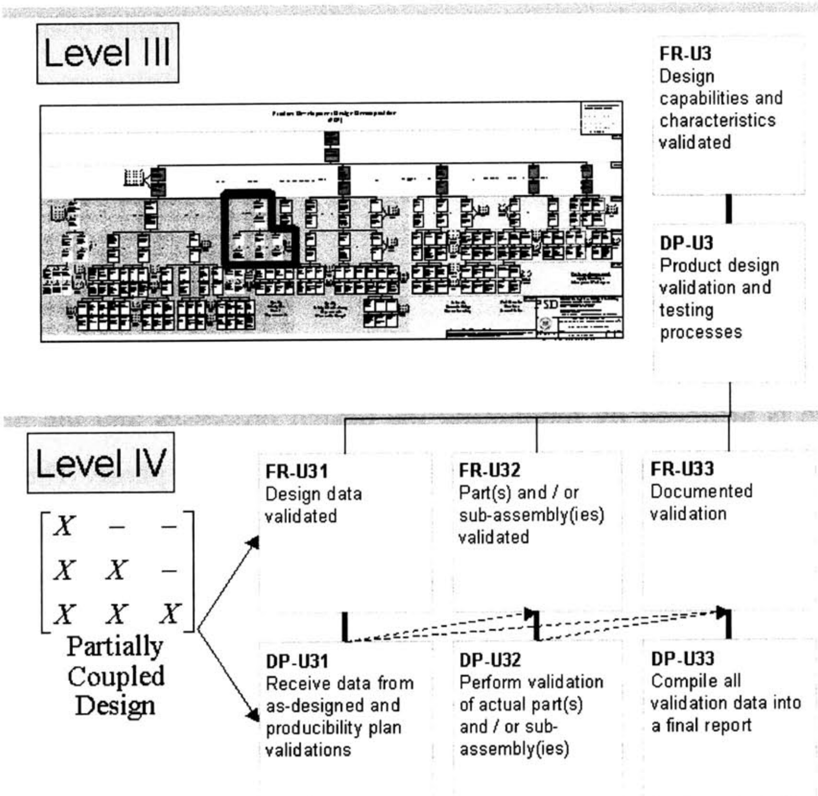


Figure 23 - Validation of Design Capabilities and Characteristics

The first FR-DP pair in Figure 23, contains a crucial objective to have the design data validated by receiving and comparing the data from the designers as the product was intended to be designed and the actual validation from the producibility plan from the manufacturing engineers. Once the data are obtained and verified with the producibility plan, the next functional requirement, *FR-U32* is achieved by actual validation of the part(s) and/or sub-assembly(ies). This FR can be achieved by ensuring that hardware makers/buyers can build and deliver the 1st article parts and the part can be used to obtain accurate validation data on the actual part that can be compared with the metrics established for acceptance. The third FR-DP ensures all the testing; validation and comparisons of part(s) and/or sub-assembly(ies) are documented into a final report for the end user to utilize and per government requirements.

The decomposition in Figure 23 is a partially coupled design as seen in the lower-triangular matrix, which implies that path dependency exists from left to right. This is also an acceptable design following axiomatic design [Suh, 1999] methodology.

7.1.4 Ensure contract obligations are delivered and fulfilled (FR-U4)

This functional requirement has been developed to ensure that all obligations that were agreed upon on the contract with the external customer are successfully delivered and fulfilled. This FR-DP pair completes the Quality – Satisfying End User's Requirements branch as specified in the PD^3.

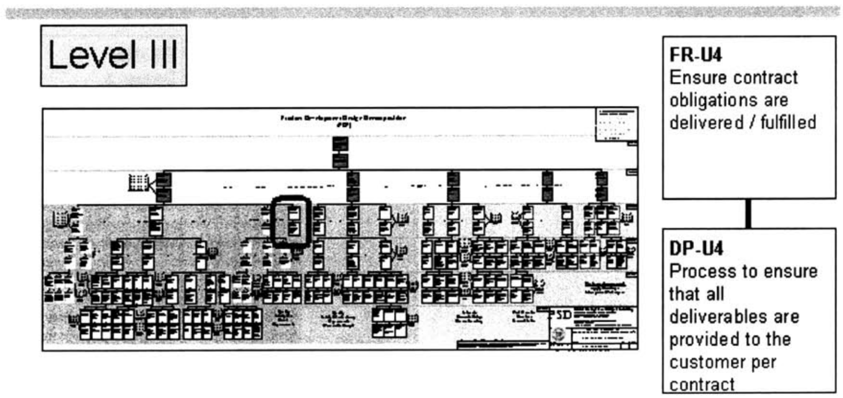


Figure 24 - Contract Obligations are Delivered and Fulfilled

7.2 Quality – Satisfy Manufacturing Requirements (FR-012)

The second high-level, *FR-012: Design a producible product that satisfies the internal customer requirements* is achieved with *DP-012: Product design that is manufacturable/producible*. The previous section 7.1 described the objectives and means to obtain a product design that would satisfy the external customer requirements. This section will now focus on one of the internal customers of product development: manufacturing engineering. At the heart of achieving a producible product is the utilization of design for manufacturing (DFM) [Swift, 1987] and design for assembly (DFA) [Boothroyd, Dewhurst, 1989]. Although there are other DFX's that have been developed lately (such as DFT, design for test) [Turino, 1990], this thesis focuses only on

DFM and DFA because they are considered more significant than the other DFX's developed recently. Another high-level functional requirement that is included in this branch and is required to achieve for the designers to implement both DFM and DFA is *FR-E1: Understand and document manufacturing processes and process capabilities*. It is imperative that the design engineers have knowledge and understand the process capabilities of the existing process. Also, it is beneficial to the achievement of the high-level objective of designing a producible product if the design engineer is also aware of new process capabilities that can be added to the existing production system without altering or adding too much cost to the entire system. The final functional requirement that is required to achieve a producible product is the validation of producibility. The decomposition of *FR-012: Design a producible product that satisfies the internal customer requirements*, is illustrated below in Figure 25.

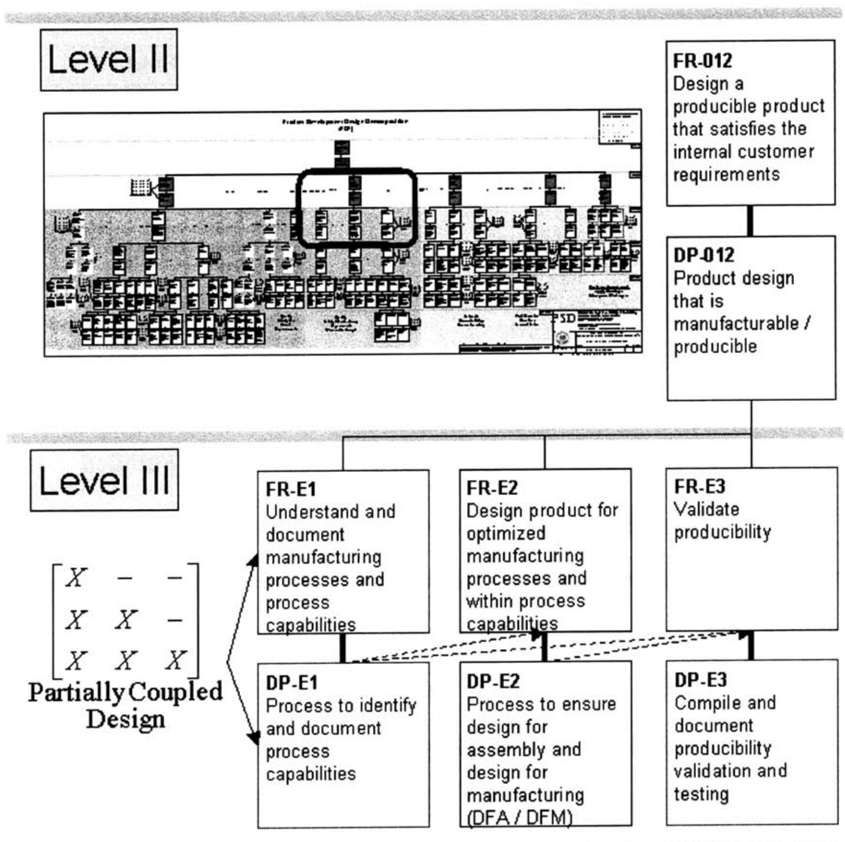


Figure 25 - Quality - Satisfy Manufacturing Requirements

The design matrix included in Figure 25 shows there will also be a path dependency in the second branch of the PD³. This means that *DP-E1* affects indirectly both *FR-E2* and *FR-E3*, while *DP-E2* affects *FR-E3* indirectly. This is an acceptable design and is further explained in the following sub-sections.

7.2.1 Understand manufacturing processes and process capabilities (FR-E1)

At the beginning of this chapter, it was discussed why knowledge of process capabilities by the designer is very important. In fact, Figure 18, depicts the situation that occurs when the design engineer is unaware of the process capabilities of the existing production system, and the resulting non-value added work in the form of re-work. It is then necessary for any enterprise to make their design engineers aware of current manufacturing processes and their capabilities. The means to achieve *FR-E1* then becomes *DP-E1: Process to identify and document process capabilities*. This FR-DP pair can be further decomposed into the actual activities of identifying process capabilities, organizing, and making these process capabilities easily accessible to the design engineer. Although this FR-DP pair is not decomposed further, a lower-level DP to this FR could be an easily accessible and web-enabled process capability database that is constantly being updated. Figure 26 illustrates where this FR-DP pair lies within the PD^3.

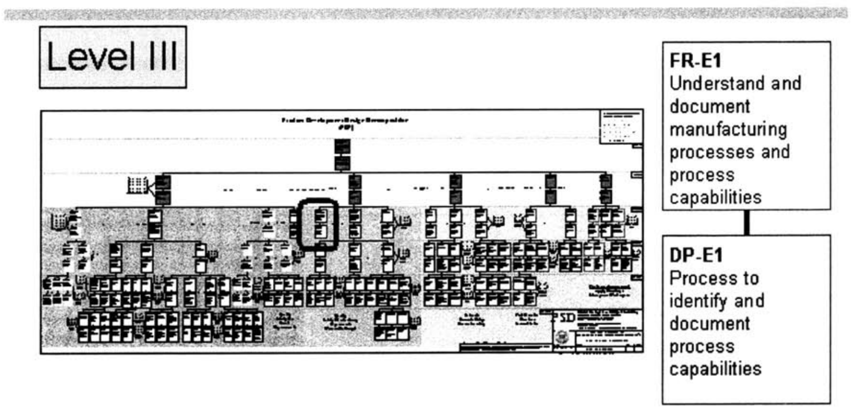


Figure 26 - Understand Manufacturing Processes and Process Capabilities

7.2.2 Product is Optimized for Manufacturing Processes within Process Capabilities (FR-E2)

As mentioned at the beginning of section 7.2, at the forefront of developing a producible product, is the utilization of techniques that have been developed recently such as design for manufacturing (DFM) [Swift, 1987] and design for assembly (DFA) [Boothroyd, Dewhurst, 1989]. This sub-section will go over some of the functional requirements that are necessary to achieve in order to design a product that is optimized for existing manufacturing processes.

Figure 27 shows the decomposition of *FR-E2* into three lower-level FRs, starting with *FR-E21: Optimize assembly and sub-assembly plan* which looks into the assembly process of the product or components and the process or plan that will be developed to optimize the assembly. The second lower-level FR, *FR-E22: Optimize details for assembly and sub-assemblies*, looks at the actual parts and its details in order to understand how to design them for assembly and manufacturing. Finally, the third FR-DP pair looks at the "make or buy" process for the selection of components and materials.

Focusing on the first lower-level functional requirement, *FR-E21*, the design parameter describes the application of optimum assembly and sub-assembly capabilities to optimize the assembly and sub-assembly plan. This FR is achieved by understanding the various assembly process candidates that can be used for the component or part being designed. The design engineer is responsible for studying new assembly research to add to the various possible assembly methods. Once the various possible assembly methods are well understood, the design engineer should conduct trade studies and development testing and therefore attempt to design the component or part to conform to the best assembly process.

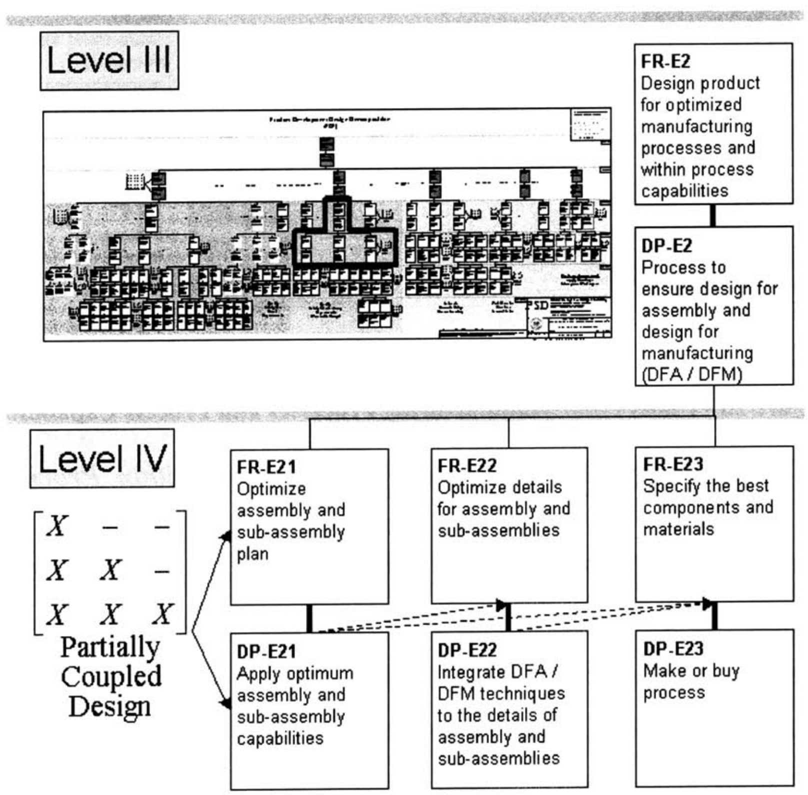


Figure 27 - Design is Optimized for Mfg. Processes and within Process Capabilities

Finally, the design engineer must validate the assembly process through actual assembly testing before providing the design and assembly process to the manufacturing engineer.

The second lower-level functional requirement, *FR-E22*, describes the need to apply design for assembly and manufacturing (DFA/M) techniques to the details of the assemblies and sub-assemblies. In the aerospace industry, this need to apply DFA/M techniques translates into combining non-moving parts into one single part when it is practical to do so, therefore, optimizing the part count of a product. Ideally, the designer's objective is to minimize the part count; however, sometimes that approach will go against your high-level objective of having a producible product if having the minimal number of parts will hinder your production (i.e. more defective parts). Also, in the aerospace industry, tooling is considered a high percentage of the total costs to produce an aircraft, and therefore, reducing the amount of assembly tooling needed becomes another functional requirement. Integrating self-locating features and tooling into individual parts can satisfy this requirement.

The third and final lower-level functional requirement of this branch is *FR-E23: Specify the best components and materials*. This FR is achieved with *DP-E23: Make or buy process*, which specifies that an efficient "make or buy" process is needed in a corporation for it to be able to specify the best components and materials for the product being produced. This FR-DP pair can be decomposed even further to show more detail on how to achieve a world-class "make or buy" process. The first FR could be to have a working knowledge of the providers/suppliers capability by maintaining databases of suppliers and their capability. Also, when a "buy" decision is reached, the design engineer should attempt to utilize "off-the-shelf" parts for the product. Specifying low risk part fabrication and manufacturing is another FR that can be satisfied by utilizing proven, low risk manufacturing processes.

The design matrix included in Figure 27 shows there will also be a path dependency in the lower levels of the PD^3. This is a partially coupled matrix, which is an acceptable design; however, *DP-E21* affects *FR-E22* and *FR-E23*; and *DP-E22* affects *FR-E23* and therefore there's a path dependency from left to right.

7.2.3 Validate Producibility (FR-E3)

The third and final high-level FR for the second branch of the PD^3 is *FR-E3: Validate producibility* and can be seen in Figure 28. This FR-DP pair is tied directly to its higher-level FR by stating that producibility requires to be validated by testing before full-scale production begins. This FR is important because it avoids unnecessary costs in production if the assembly or manufacturing process is not validated first. This FR-DP pair is also the tie-in, or hook to the manufacturing system design decomposition or MSDD [Cochran, Arinez, Duda, Linck, 2000] that is described briefly in chapter 5.

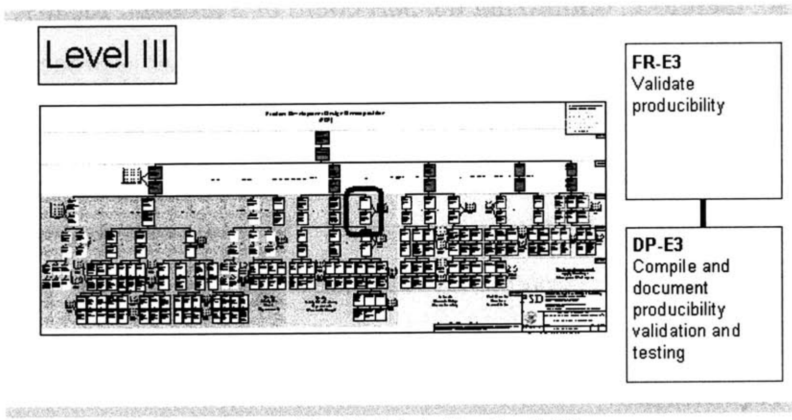


Figure 28 - Validate Producibility

7.3 Schedule – Eliminate Delays and Reduce Inventory (FR-013)

The third high-level objective to achieve a successful product is to reduce the amount of time it takes to design the product. This FR is key to the success of the product, especially in the aerospace industry where the development of a military aircraft may take years or even decades. There are many reasons why the development time of an aircraft takes so much time; however, the main reason is that airplanes are very complex products with thousands of parts. Nevertheless, there is a lot of room for improvement in the development process to reduce the time it takes to design a product, starting from reduction of waiting time, walking distances, re-iterations in the design and basically any form of non-value adding tasks and activities.

The high-level design parameter that will achieve this FR is *DP-013: Standardized design processes*. What this DP intends to define is that by having standardized processes in the development phase, the customer need date will be met, because the development time is standard, and therefore the time taken to develop a product should be visible to the end user. Also, a standardized process ensures that streamlining the process and eliminating waiting time and walking distances will minimize the non-value added tasks and activities. Finally, a standardized design process can help minimize the reiterations in the development process and hence reduce the overall time it takes to develop the product. Figure 29 shows this high-level FR-DP pair and its subsequent decomposition into three FR-DP pairs.

Figure 29 also shows an un-coupled design matrix, which is the best design scenario. The significance of an uncoupled design is that the DPs only affect their corresponding FRs and do not affect any of the other FRs.

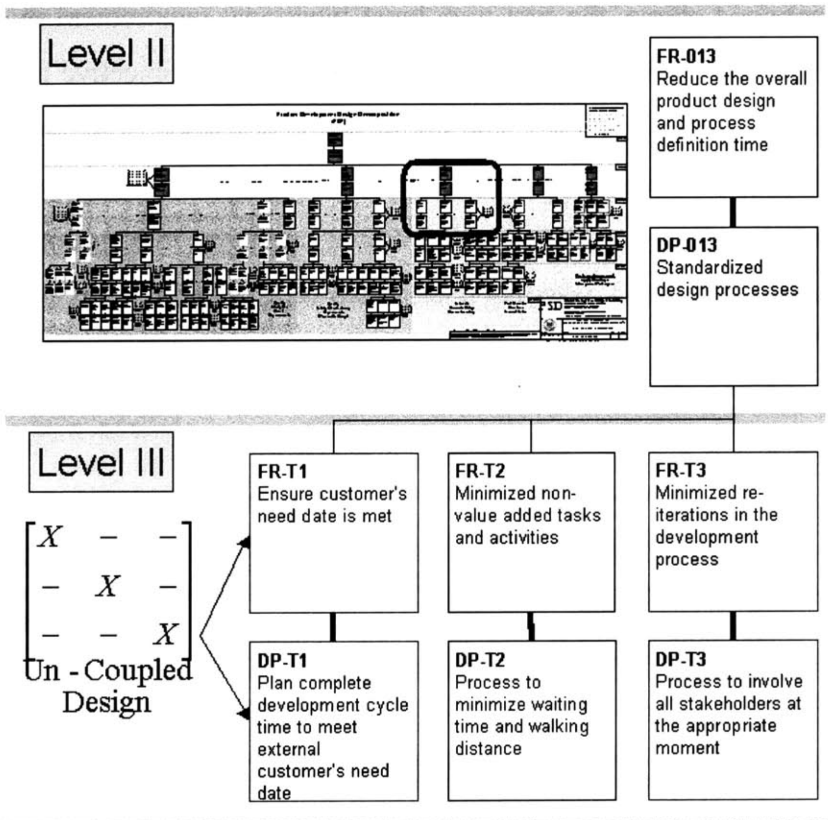


Figure 29 - Schedule, Reduce Overall Product Development Time

The top-level functional requirement in Figure 29 is decomposed into three FR-DP pairs. The first functional requirement is *FR-T1*, which states that the customer need's date needs to be met. This FR is closely tied with satisfying the external customer requirements because the due date is usually also a customer requirement and this relationship is shown in the PD^3 in the design matrix at level II.

The second functional requirement or *FR-T2* describes the need to minimize as much as possible the non-value added tasks and activities. Once again, these tasks and activities do not add value to the product. The tasks do not change the shape, form, or function of the product and are usually divided into two groups: waiting and walking distance.

Finally, the third functional requirement or *FR-T3* has as objective to minimize the reiterations in the design process. These reiterations cause re-work and convert the originally value-added work into non-value added work. The following sub-sections will discuss in detail *FR-T1*, *FR-T2*, and *FR-T3*.

7.3.1 Ensure Customer's Need Date is Met (FR-T1)

As mentioned above, the first high-level functional requirement in the Schedule branch deals with the customer requirement of due date. The objective is to ensure that the customer's need date is achieved and the means is described as the design parameter *DP-T1: Plan complete development cycle time to meet external customer's need date.* This FR-DP pair becomes a matter of project management and making sure that the entire development cycle is planned including unexpected tasks, activities and delays.

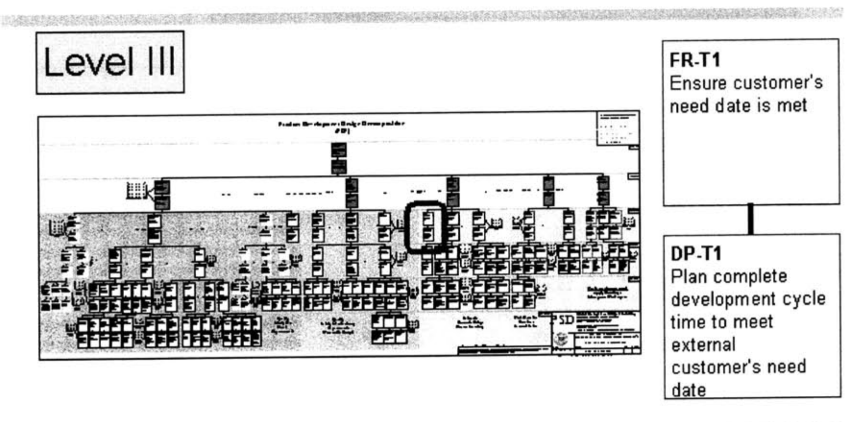


Figure 30 - Ensure Customer's Need Date is Met

7.3.2 Minimize Non-Value Added Tasks and Activities (FR-T2)

Non-value added tasks and activities do not change the shape, form or function of a product. Non-value added tasks could be divided into two different types: waiting time and unnecessary walking. Also, unnecessary inventory or designs being done at an early stage become non-value added because the design might change and must be changed. Based on the non-value added tasks, the high-level functional requirement, *FR-T2*, has been decomposed into three lower-level functional requirements that can be seen in Figure 31.

DP-T21: Implement just-in-time work schedule is the DP that satisfies the objective *FR-T21: Minimize unnecessary inventory (designs are not done too early)*. This FR-DP pair has been included as part of the schedule branch to aid in having standardized design processes by implementing just-in-time work schedules. This DP is similar to the just-in-time concept used in the Toyota Production System (TPS), but instead of physical parts the product are designs that are developed during the product development process. The design engineer should have a balanced work-loop in such a way that there is no inventory accumulating when he/she is working on another design, yet when the design is complete the design engineer will have another design to work on.

A designer waiting on product designs is the opposite of having inventory accumulating. This event is described in the second lower-level functional requirement or *FR-T22: Minimized waiting time (designs are not done too late)* and it is paired with the design parameter *DP-T22: Have latest design and resources available at all times to all stakeholders and team members,* that will achieve such objective. It is crucial to note that not only does a design need to be available to the design engineers. The necessary resources so that the design engineer can begin working on the design immediately are also needed. This objective can be decomposed further to illustrate that resources need to be scheduled so that they're available when needed. Also, it is at this point where standardized tools (software, hardware, design policies, etc.) should be implemented to minimize the time spent on converting data from one system to another. Finally, a lower-level objective of minimizing waiting time due to lack of training can be satisfied by supplying standardized training for all team members.

The third lower-level functional requirement of this branch is *FR-T23: Minimized walking distance*. This FR is achieved with *DP-T23: Actual, dynamic and/or virtual collocation*, which specifies that a variety of physical and non-physical collocations for the various team members of an integrated product team is needed in a corporation to minimize the distance the team members must walk. If the interaction among team members is high, then an actual collocation is advised. If the interaction is temporary, then a dynamic collocation is a better arrangement. Finally, a virtual collocation is recommended if the interaction is limited. With the advances in technology, even if the interactions are frequent, virtual collocations will begin to make more business sense.

The design matrix in Figure 31 depicts an un-coupled design. Functional independence is achieved in this branch of the PD³ and therefore, the DPs only affect their respective FRs, making it a better design.

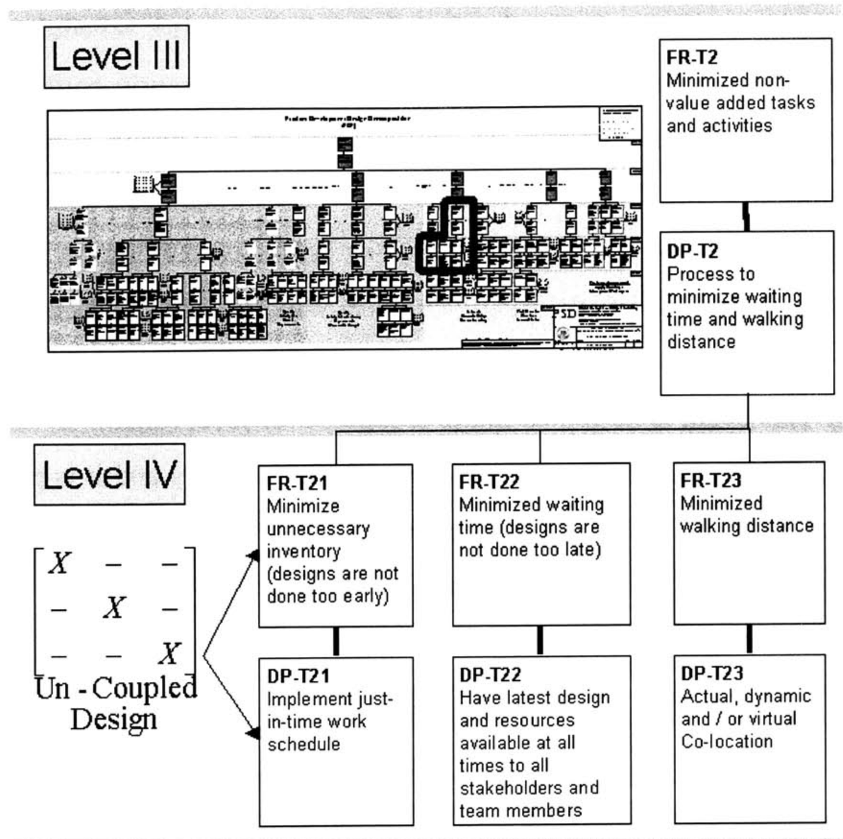
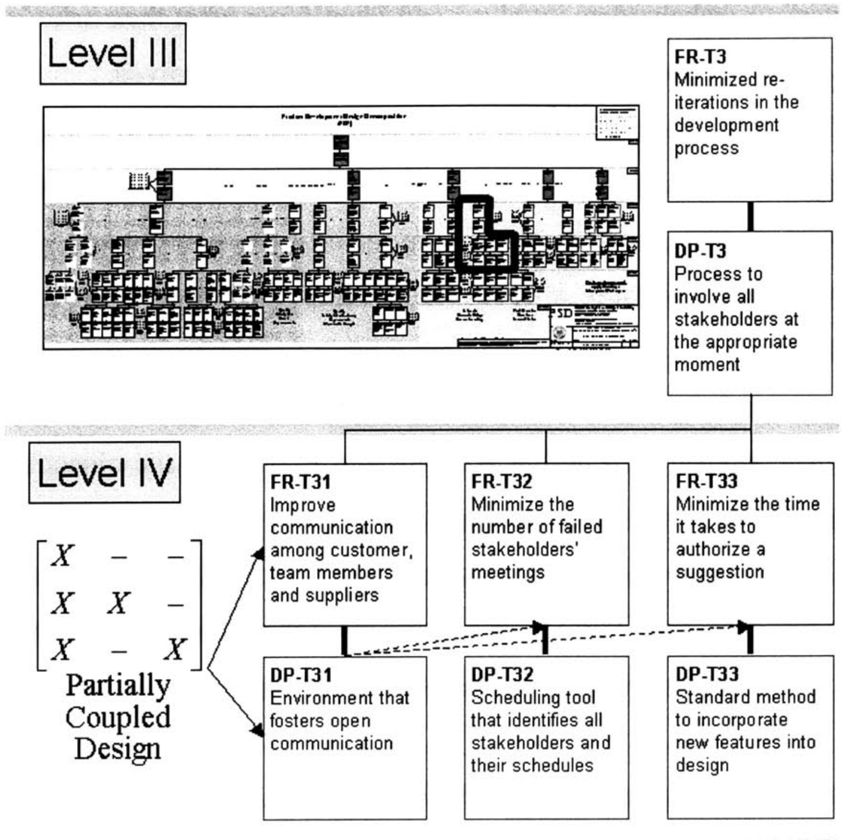


Figure 31 - Minimize Non-Value Added Tasks and Activities

7.3.3 Minimize Reiterations in the Development Process (FR-T3)

Initially, one of the main reasons why *FR-T3: Minimize reiterations in the development process* was included in the PD³ was to minimize the many failed meetings at Northrop-Grumman Corporation. There was difficulty when attempting to obtain the agreement of all the stakeholders to meet at a certain time and place due to various reasons, but mostly because some stakeholders were not available during the original selected meeting time. This problem often postponed the development phase and was a major cause of having engineers work overtime to meet deadlines.

This objective or FR was then expanded to include an even more important objective: communication among stakeholders. This new objective of increased communication was seen as an enterprise objective and should be considered an objective that has a significant impact on the time it takes to develop a product. The other FR that was included in this branch was *FR-T33: Minimize the time it takes to authorize a good suggestion.*



$$\begin{bmatrix} X & - & - \\ X & X & - \\ X & - & X \end{bmatrix}$$

Figure 32 - Minimize Re-iterations in the Development Process

The first lower-level functional requirement, *FR-T31: Improve communication among customer, team members and suppliers* looks at the entire supply chain, from the suppliers to the end user. In this case the design parameter developed to achieve this objective was *DP-T31: Environment that fosters open communication.* More specifically, in order to improve communication with the customer, the ideal solution is to have a representative of the enterprise located at the customer's site and vice versa. To improve communication among team members, team meetings and collocations should be arranged as a design parameter. Finally, to improve communication with the suppliers, as with the customer, it is ideal to have a representative of the enterprise at the suppliers' location and vice versa, plus the enterprise needs to involve the supplier at an early stage in the development process.

The second lower-level functional requirement, *FR-T32: Minimize the number of failed stakeholders' meetings* is meant to ensure that all stakeholders' are available when a meeting is required. As a design parameter, *DP-T32: Scheduling tool that identifies all stakeholders and their schedules* was developed. In this case, using technology to help identify the various stakeholders involved and identifying what their schedules look like will help in scheduling the best time and place for everyone involved.

The third lower-level objective is tied to continuous improvement. A corporation cannot continue to utilize the same processes over and over without improving them or utilizing new technologies to improve the quality of the product, make it more producible, minimize the time it takes to develop the product, or making it more profitable. This objective deals with the time it takes to implement a suggestion that will make a product more successful. As a design parameter, *DP-T33: Standard method to incorporate new features into design* was selected to achieve the objective or *FR-T33: Minimize time it takes to authorize a suggestion.*

Finally, in Figure 32 a design matrix that depicts a partially coupled design is illustrated. In this case, only *DP-T31* affects the other two functional requirements but the other two do not affect any other FRs, except their corresponding functional requirement.

*7.4 Cost – **Ensure Product is Profitable (FR-014)***

The three previous branches, Quality – End User, Quality – Manufacturing, and Schedule, dealt with costs in a unique way. Although the objectives were geared towards satisfying customer requirements, making a producible product or designing the product in the minimum amount of time, all of these FRs translate to capital. If customer requirements are not satisfied, then the customer will not be willing to pay as much for the product. If the product itself is not producible, then costs will be incurred in the form of re-work, scrap, defects, etc. Finally, if the time it takes to produce the design becomes longer, the more costs will be incurred in the form of direct and indirect labor. This fourth branch looks at the costs that were not taken into consideration by the first three branches. Specifically it looks into how the budget is dispersed for both direct and indirect labor.

The top-level functional requirement *FR-014: Ensure product is profitable* is decomposed into two FRs: *FR-C1: Optimized direct product development cost* and *FR-C2: Minimized the indirect product development cost.* It is necessary to make the reader aware that the word "optimize" was used for direct product development cost because if cost is minimized, there is a higher probability that the best product design might not be achieved due to the fact that employees will attempt to minimize costs at every respect compromising the quality of the product. However, the word "minimize" was used for the indirect product development cost because this is considered non-value added work and therefore does not change the shape, form or function of the product and hence does not affect the quality of the product.

Figure 33 shows the decomposition of this high-level FR and where this FR belongs among the entire PD³. The reader should note the partially coupled design matrix in level III that describes the affect that *DP-C1: Apply cost/schedule control system (C/SCS) management system* has on *FR-C2*. Also, the chosen design parameter for *FR-C2* is *DP-C2: Process to eliminate non-value adding tasks*.

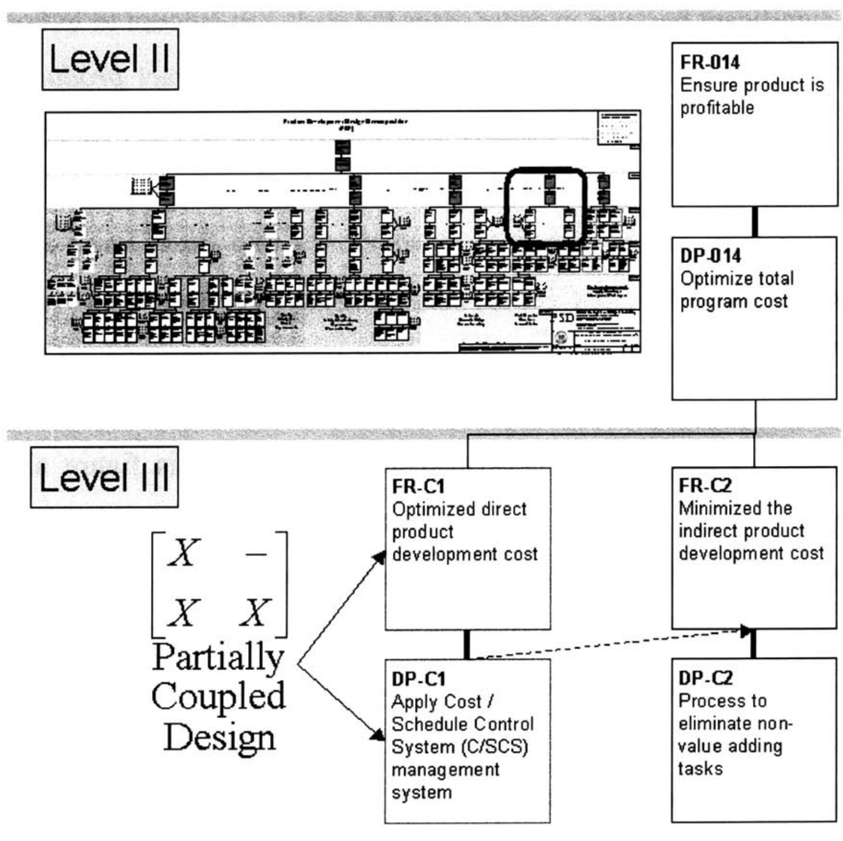


Figure 33 - Ensure Product is Profitable

The Cost/Schedule Control System (C/SCS) is a set of criteria specified by the Federal Government for reporting project schedule and financial information. C/SCS was developed by the Air Force to help monitor contract cost and performance for large-scale system acquisitions. The C/SCS has become a requirement for corporations that have a government contract and is considered by many to be a very good system to track costs and schedule. This system was chosen as a design parameter because the C/SCS helps management track the amount of capital spent on the project and compare this capital to the planned capital expenditure as well as comparing the schedule of the project and how well is progressing.

The following sub-sections describe in more detail the level III and level IV FR-DP pairs of the cost reduction branch.

7.4.1 Optimized Direct Product Development Cost (FR-C1)

Optimizing the direct cost of product development is a high priority in many industries, especially in industries where this cost accounts for a high percentage of the total cost of goods sold (COGS). In the aerospace industry, this is not the case, however, the costs are significant because in some cases the costs can amount to billions of dollars. The high-level objective then becomes *FR-C1: Optimized direct product development cost* and the design parameter to achieve this objective is *DP-C1: Apply cost/schedule control system (C/SCS) management system.*

This high-level objective can be decomposed into three lower-level functional requirements, starting with *FR-C11: Optimized budget for planned development tasks*, then *FR-C12: Appropriate funding at the various stages of development* and finally *FR-C13: Ensure cost effectiveness is being achieved.* These functional requirements and their respective design parameters are illustrated in Figure 34. This figure also contains a partially coupled design matrix with a lower triangular feature, which implies that the design parameters affect the sub-sequent functional requirements.

The objective of the first lower-level functional requirement, *FR-C11*, is to look at the planned development tasks and allocate the appropriate funding to every task. The means to achieving this objective is described as *DP-C11: Procedure to appropriately allocate budget for planned development tasks*. This FR-DP pair deals with the issue of programs constantly being over-budget in the aerospace industry. One of the main reasons why this occurs is because of a poor estimating process and because unforeseen tasks and activities were not accounted for. The logic behind *DP-C11* is to implement a good cost and/or hours estimating process for every development task and also to include some management reserve funds for tasks and activities that are unforeseen.

Once the objective of allocating the budget for the planned development tasks has been accomplished, the appropriate funding has to be distributed at the right time. This functional requirement seen as *FR-C12* is achieved with the design parameter *DP-C12: Distributed budget against planned development tasks per schedule*. This FR-DP pair looks at the distribution of funds to the various integrated product teams during the various stages of product development. The distribution should be done based on the schedule and if the schedule changes so should the distribution of funds.

The final lower-level FR-DP pair, *FR-C13*, ensures that cost effectiveness is being achieved by means of *DP-C13: Conduct regular cost reviews and modify business plan to adapt to any changes*. Basically, what this FR-DP pair intends to accomplish is to keep all the costs on schedule by adapting to any changes in the development phase. The business plan also requires to be modified if there's any change in the product development tasks.

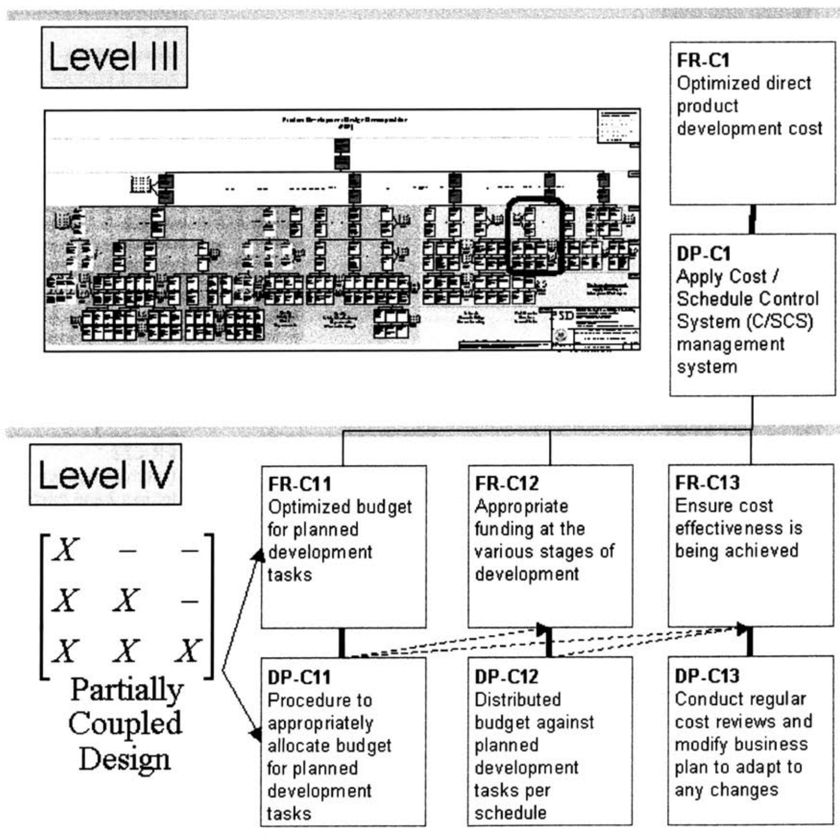


Figure 34 - Optimized Direct Product Development Cost

The above decomposition looked at direct product development costs only. The following sub-section will describe the objective of making sure the product is profitable by minimizing the indirect product development cost.

7.4.2 Minimize the Indirect Product Development Cost (FR-C2)

This decomposition of the cost reduction branch deals with the indirect costs produced by indirect labor (tasks and activities). These indirect costs are considered non-value added since these costs do not change the shape, form or function of the final product. There are two different types of indirect product development costs that can be minimized. The first type is the costs associated with indirect tasks and the second type is costs associated with overhead costs such as supplies, etc.

This functional requirement, *FR-C2: Minimized the indirect product development cost*, is achieved by implementing its design parameter or *DP-C2: Process to eliminate non-value adding tasks.*

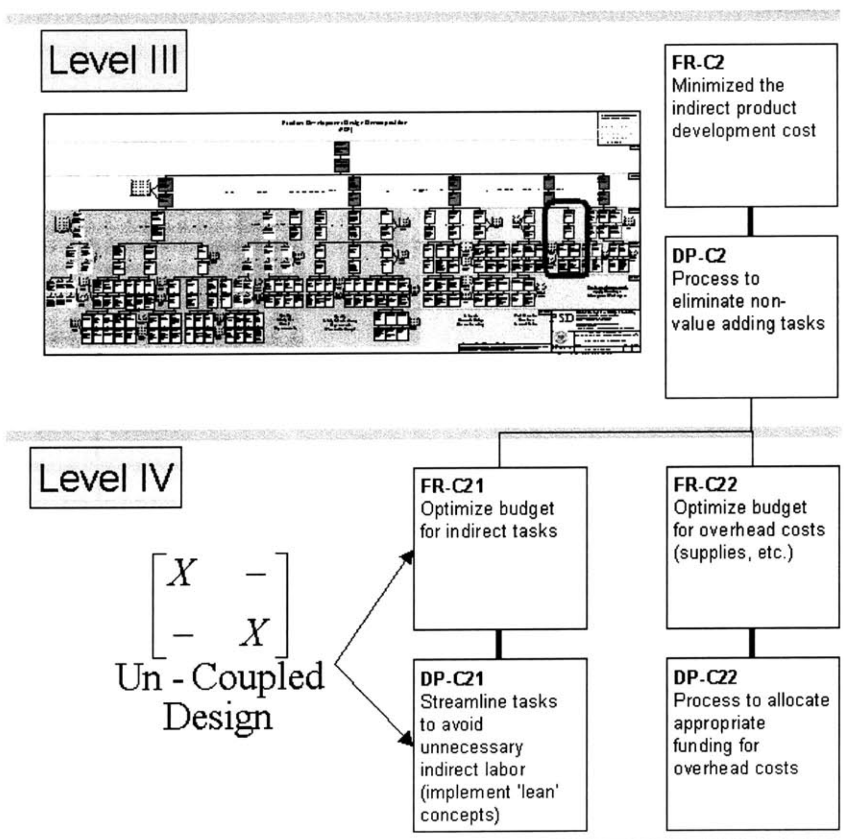


Figure 35 - Minimize the Indirect Product Development Cost

As mentioned above, the first type of indirect development cost is represented by the first lower-level functional requirement, or *FR-C21: Optimize budget for indirect tasks*. This FR states the need to optimize the budget for indirect tasks by streamlining tasks and applying 'lean' concepts to the development process that relate to indirect tasks. For example, the purchasing department is considered an indirect task and should, therefore, be streamlined so that only the required personnel are in charge of the purchasing.

The second lower-level functional requirement, *FR-C22: Optimize budget for overhead costs (supplies, etc.)* is achieved through *DP-C22: Process to allocate appropriate funding for overhead costs*. This FR-DP pair attacks the misuse of supplies and overhead tools. The design parameter intends to tell the user to implement a system or process that allocates appropriate funding or even allocate the appropriate supplies to the various departments that require these supplies.

7.5 Continuous Improvement – Process Improvement Initiatives (FR-015)

The fifth and last branch of the product development design decomposition (PD^3), looks at the continuous improvement activities that a corporation must implement to stay competitive and continue to produce successful products. This branch was included in the PD^3 to ensure that this decomposition becomes a living document. As new techniques and technologies are developed, a replacement and/or addition of FR-DP pairs should be done to maintain the PD^3 current and more efficient.

The PD^3 as mentioned before, was developed for Northrop-Grumman corporation and therefore, the design parameter that achieves *FR-015: Ensure continuous improvement*, is described as *DP-015: Northrop Grumman's process improvement initiative*. This FR-DP pair and its decomposition can be seen in Figure 36. Also, a partially coupled design matrix shows that the first design parameter, *DP-K1*, affects the second functional requirement, *FR-K2*, which is described below.

The top-level functional requirement is decomposed into three functional requirements. The first objective is *FR-K1* and this FR has as objective to ensure that useful knowledge is identified, captured, and organized accurately. The second functional requirement has as objective to allow the sharing, adoption and utilization of the captured knowledge. Finally, the third objective is to improve the effectiveness of product managers.

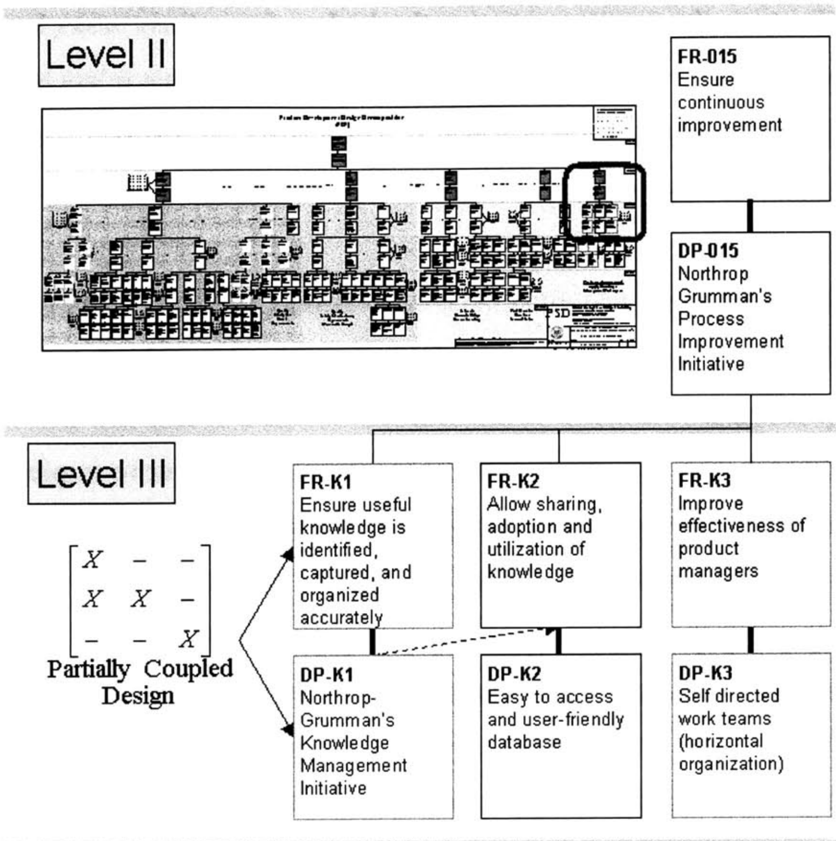


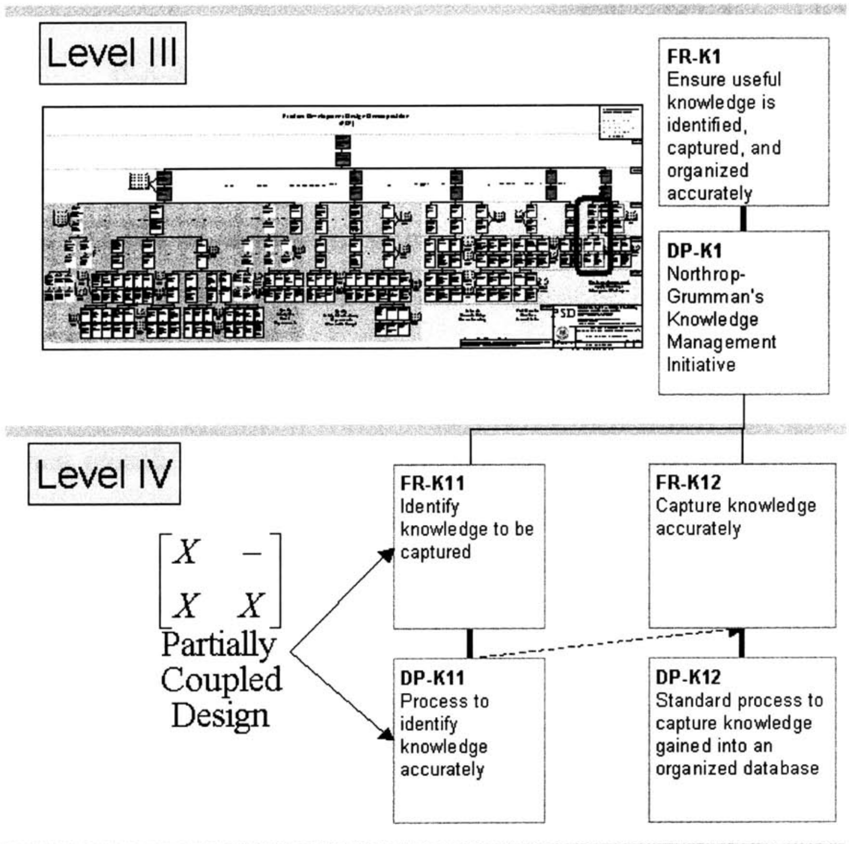
Figure 36 - Ensure Continuous Improvement

The corresponding design parameters for these functional requirements are: *DP-K1: Northrop-Grumman's Knowledge Management Initiative*, *DP-K2: Easy to access and user-friendly database*, and finally, *DP-K3: Self directed work teams (horizontal organization)*. These FR-DP pairs are discussed in more detail below starting with the first functional requirement and its decomposition into lower-level functional requirements.

7.5.1 Ensure Useful Knowledge is Identified, Captured, and Organized Accurately (FR-K1)

The reason for this functional requirement is to have a working database of processes, products and any other type of useful information that could help the user to make a better product. However, this database must be controlled and overseen with critical discipline. The users should be clear on what is "useful knowledge" and what processes are in place to capture that knowledge and organizing this knowledge accurately. The design parameter assigned to this functional requirement is *DP-K1: Northrop-Grumman's Knowledge Management initiative*, which is an initiative within NGC to retain the best knowledge from their various programs and applying to new programs.

The decomposition of *FR-K1* can be seen in Figure 37, where there's also a schematic view of the entire PD^3 and a partially coupled design matrix. This matrix implies that *DP-K11* affects the functional requirement *FR-K12*.



$$\begin{bmatrix} X & - \\ X & X \end{bmatrix}$$

Figure 37 - Ensure Knowledge is Identified, Captured, and Organized Accurately

The first lower-level functional requirement, *FR-K11: Identify knowledge to be captured* looks into attempting to identify what knowledge is considered useful and worthy to be captured. In other words, there's no need to capture knowledge that is not useful and will not have a useful application in the future. The design parameter assigned to this functional requirement is *DP-K11: Process to identify knowledge accurately.*

The second lower level functional requirement of the continuous improvement branch looks into the capturing of the useful information. Once the knowledge has been identified then *FR-K11* has been satisfied and now *FR-K12: Capture knowledge* *accurately* must be satisfied. Here the design parameter is *DP-K12: Standard process to capture knowledge gained into an organized database.* This DP looks into the information and states that the information has to be identified first and then should be captured in an easy to use and organized database.

It is critical to note that this information is useless unless the stakeholders in the product development process utilize the information to improve their current processes. The next FR-DP pair will describe both the objective and the means of achieving utilization of this useful knowledge.

7.5.2 Allow Sharing, Adoption and Utilization of Knowledge (FR-K2)

In the previous sub-section, a description of how to identify and capture useful information was discussed. In this sub-section, the sharing, adoption and utilization of this knowledge is discussed. The objective is described in *FR-K2: Allow sharing, adoption and utilization of knowledge* and the means to achieving this objective is represented as *DP-K2: Easy to access and user-friendly database.* This FR-DP along with its decomposition can be seen in Figure 38. In this figure, there's also a partially coupled design matrix, which implies that the first lower-level design parameter has an indirect affect on the second lower-level functional requirement.

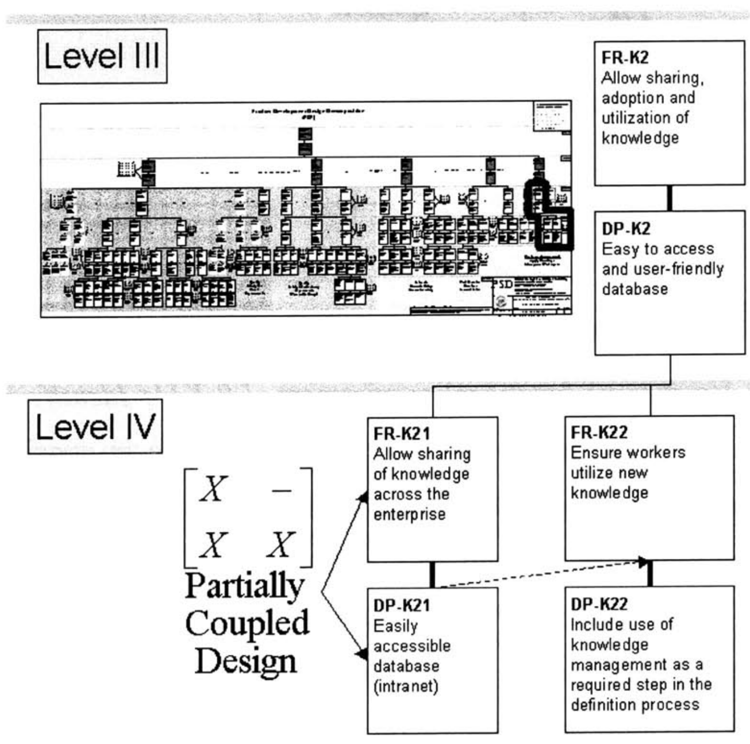


Figure 38 - Allow Sharing, Adoption and Utilization of Knowledge

The first lower-level functional requirement of this decomposition, *FR-K21: Allow sharing of knowledge across the enterprise* describes the need to have an open communication tool across the corporation so that design engineers can share their tools with manufacturing engineers and vice-versa. The design parameter that intends to accomplish this objective is *DP-K21: Easily accessible database (intranet)*. This design parameter defines that the database has to be accessible and easy-to-use for all the employees of the enterprise. This will allow for easy sharing of information.

The second lower-level functional requirement looks at the utilization of this information. It is not sufficient to identify, capture and share the useful information throughout the corporation, there's also the need to utilize this information in a productive manner that will make the product more successful, by either adding a functionality that the end-user is willing to pay for, making the product more easily producible, reducing the time to produce the design, or reducing any indirect or direct labor to the product development process.

7.5.3 Improve Effectiveness of Product Managers (FR-K3)

The final functional requirement of the continuous improvement branch has to do with the product managers and their effectiveness. The intention of this FR-DP pair is to have product managers become more efficient by managing several work teams. Training and implementing self-directed work teams can accomplish this. Currently there is one product manager for every integrated product team (IPT). Ideally, the self-directed work teams would not require a product manager to oversee their progress because of standardized work and processes that will allow the workers to know exactly their jobs.

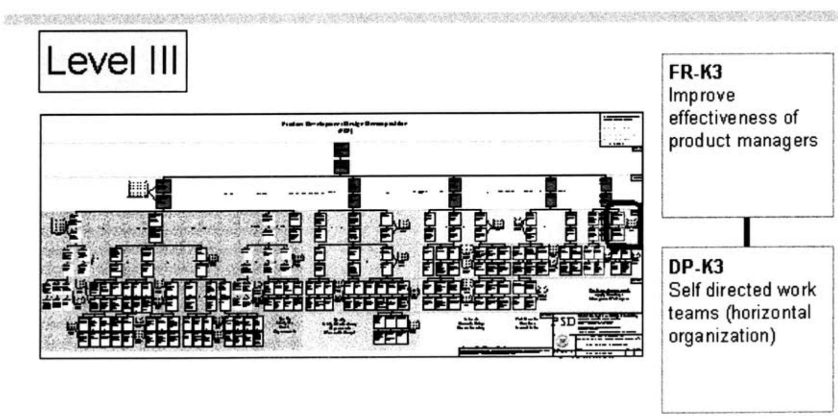


Figure 39 - Improve Effectiveness of Product Managers

The product development design decomposition (PD^3) provides a logical and systematic approach to achieving the high-level objective *FR-01: A product design and process definition that meets internal and external customer requirements*. In Chapter 6, the manufacturing system design decomposition (MSDD) describes a structured and logical approach to the design of production systems. The PD^3 takes a step backward in the life cycle of a product into the product development phase and describes the various FR-DP pairs that must be achieved to satisfy *FR-01*.

This chapter describes in detail the four different levels of FR-DP pairs (from level I to level IV). This chapter describes the logic and reasoning behind the various FRs and their corresponding DPs and how these affect subsequent FRs in other branches of the PD^3. The inclusion of design matrices for every branch of the PD^3 describes the interrelationships that occur among the various FR-DP pairs and the text in this chapter provides examples of the implementation of the DPs. Finally, this chapter describes the path-dependency of *FR-011*, *FR-012*, *FR-013*, *FR-014*, and *FR-015*. This path-dependency provides a framework to follow when implementing the PD^3.

A full design matrix for the entire PD^3 that describes the interactions between the DPs and the FRs is illustrated in appendix C. This design matrix indicates when a DP in one branch affects an FR in another branch of the PD^3. For example, it is important to know whether *DP-U22: Organize team and supply tools as required* affects *FR-C11: Optimize budget for planned development tasks* because the team and supply tools are part of the budget that must be optimized according to *FR-C11*.

PART III – EXAMPLES AND CONCLUSION

CHAPTER 8 – APPLICATION OF THE PD^3

The product development design decomposition (PD^3) was developed for Northrop-Grumman Corporation (NGC); however, the PD^3 can be easily applied to any other corporation or industry. The structured and logical approach of the PD^3 makes this decomposition applicable to other corporations and industries because none of the FR-DP pairs are NGC specific. The PD^3 is a decomposition that has as a high-level objective *FR-01: A product design and process definition that meets internal and external customer requirements*, which is the objective of any product development organization in any industry.

The main point to emphasize when implementing the PD^3 is the high-level objectives and the means to achieve the desired objectives. It is also important to note that the PD^3 is a decomposition, and that the users of this decomposition can modify this document as required.

As a program manager or the lead manager for the development of a product, the PD^3 can be used as a guide or roadmap to improve the current development process or aid in the design of a new development process as described in section 8.1 and 8.2. Also, the PD^3 can be used to aid in the organizational design of the product development team as described in section 8.3.

8.1 The PD^3 as a Product Development Process Baseline

The nature of the PD^3 and the approach taken to develop this decomposition, make the PD^3 an ideal decomposition to use as a baseline for a product development process. Although the PD^3 was not designed as a process design tool and the various FRs and DPs are not arranged in a chronological manner, the PD^3 can still be used to develop the baseline of what a product development process should look like. A process design tool gives a step-by-step methodology to design a process in a chronological manner, without indicating what are the objectives of the process or the means to achieving these objectives. In contrast, the PD^3 provides all the DPs that should be implemented to design an efficient and structured product development process to assure that the high-level FRs are being satisfied.

A new venture corporation or an existing one with a new product can use the PD^3 to design their product development process. It must be noted that for any product design activity to be successful, there are five main objectives that must be satisfied:

1) Meet external customer requirements
2) Must be producible
3) Must be delivered to the customer in the expected amount of time
4) Profitability
5) Able to improve continuously

These five objectives are the top-level FRs of the PD^3. These FRs are decomposed in such a way to allow the user to see what the solutions or DPs are needed to achieve these high-level objectives. Based on this specification, the product development process can be designed so that the DPs of the PD^3 are engrained in this process and satisfies all the FRs. The first branch of the PD^3 is the *Quality – Satisfy End User Requirements* branch, and contains the DPs that design engineers should implement when developing a product. These DPs are defined under the decomposition branch of *FR-U23*. See section *7.1.2 Design product to achieve external customer's requirements (FR-U2),* for further information.

8.2 The PD^3, a Decomposition to Improve the Product Development Process

Most corporations have a product development process that has been evolving since the creation of the corporation. The implementation becomes more difficult when the product development process has been in existence for many years; however, the implementation is not impossible to accomplish. The ideal transition from the current product development process to the new product development process with the PD^3 as the baseline is to start from 'scratch' and to build completely a new product development process.

The first step to improve the current product development process is to communicate and train personnel on the use of the PD^3 and to teach them the benefits and use of the design methodology. The next step for the improvement is to look at the first branch of the PD^3 and to derive a product development process based on the DPs of this branch. The DPs in the remaining branches should be implemented to reap the additional benefits of reducing non-value adding work. An easily accessible database of process capabilities, physical collocation and design for assembly / manufacturing, are a few examples of these DPs that should be implemented. Also, a streamlined process for direct and indirect labor tasks and activities must be designed utilizing the DPs of the *Cost Reduction* branch.

It is important to reinforce to the entire product development team that the five high-level FRs must be achieved in order to provide to the customer(s) a successful product. The enterprise's development process will begin to see a positive transformation and will begin to see the benefits of implementing some of the DPs described in the PD^3 as described in Chapter 7.

8.3 The PD^3 as an Aid to Organizational Design

The PD^3 can be used as a decomposition to help a corporation design its organization. The top-level functional requirement is the responsibility of the program manager and from there on, the various FR-DP pairs can be assigned to different people in the organization. It is crucial to make sure that when a coupling occurs between two FR-DP pairs, these FR-DP pairs are assigned to the same person to avoid political conflicts and self-interest arguments among the employees.

For example, the program manager could have five employees working for him/her. Each one would be responsible for a high-level objective and the corresponding decomposition. Some of these employees would be working more closely than others, such as the quality branches employees would be working a lot closer with each other than with the employees responsible for continuous improvement.

A program manager can derive from the PD^3 an evaluation tool that will help evaluate the performance of the product development process. The PD^3 would then guide the program manager to effectively identify the DPs that have not been implemented and use any corrective measures to achieve the FRs of the PD^3.

CHAPTER 9 – CONCLUSION AND FUTURE WORK/RESEARCH

9.1 Conclusion

A product must be designed rationally and logically to achieve a set of functional requirements. The resulting product design will depend heavily on the different functional requirements chosen to satisfy all customers. In this case, a decomposition called the product development design decomposition (PD^3) was developed to achieve five product design related functional requirements (FRs).

The PD^3 is a decomposition designed for upper management to aid in the design of their product development process focusing on five key issues: 1) how well the product satisfies the external customer requirements; 2) designing/developing a producible product that is defect free and low cost; 3) the time it takes to develop a new product; 4) the cost to develop the new product; and 5) focusing on continuous improvement.

The end result, when following the design methodology of the PD^3, is a successful product design that achieves all the FRs stated in the PD^3. The PD^3 will help an organization design their development process in a streamlined fashion with little or no redundancies and with a small percentage of non-value added activities. Moreover, the most important improvement that the PD^3 gives its user is visibility and control over the product development process. The PD^3 accomplishes this objective by implementing standardized processes with minimal deviations in quality, cost, and schedule. The PD^3 also provides visibility of process capabilities, enabling the design engineers to design producible products.

The PD^3 also provides the user with a decomposition to see the relationships and interactions between product design and the manufacturing system. The PD^3 accomplishes this objective by allowing the designer to interact with the manufacturing engineer and improve communications across the supply chain. The PD^3 also shows the various interactions between lower-level FRs and DPs. In conclusion, it must be emphasized that the PD^3 is a living document and should be treated as such by continuously improving its content, either by replacing outdated FR-DP pairs, modifying them or adding new FR-DP pairs to the existing branches of the PD^3. Improvements to the PD^3 will allow the PD^3 to stay current as new technologies and concepts are developed. For example, if the technology for virtual meetings is greatly enhanced, then the DP of having physical collocations will be obsolete and the DP should be replaced with a newer DP that defines virtual meetings as the means to achieving better communication among team members.

9.2 Future Work/Research

The next step for this research is to develop performance measures (PMs) for every FR-DP pair. The PMs will measure how well the FRs are being satisfied through the implementation of the DPs. The PMs can also aid in the assessment of the employees' performance when a certain FR-DP is assigned to an employee.

The PD^3 requires an evaluation tool to validate its applicability in various industries. The evaluation tool will aid corporations in identifying the areas for improvement by rating how well the solution is satisfying a certain FR-DP pair.

Finally, a practical addition to the PD^3 would be a deployment steps framework. This framework should be an easy to follow step-by-step tool to aid corporations in the implementation of the DPs of the PD^3. The objective of developing a deployment steps framework can be achieved by designing a structured and logical sequence of events that must occur to satisfy the various FRs in the PD^3.

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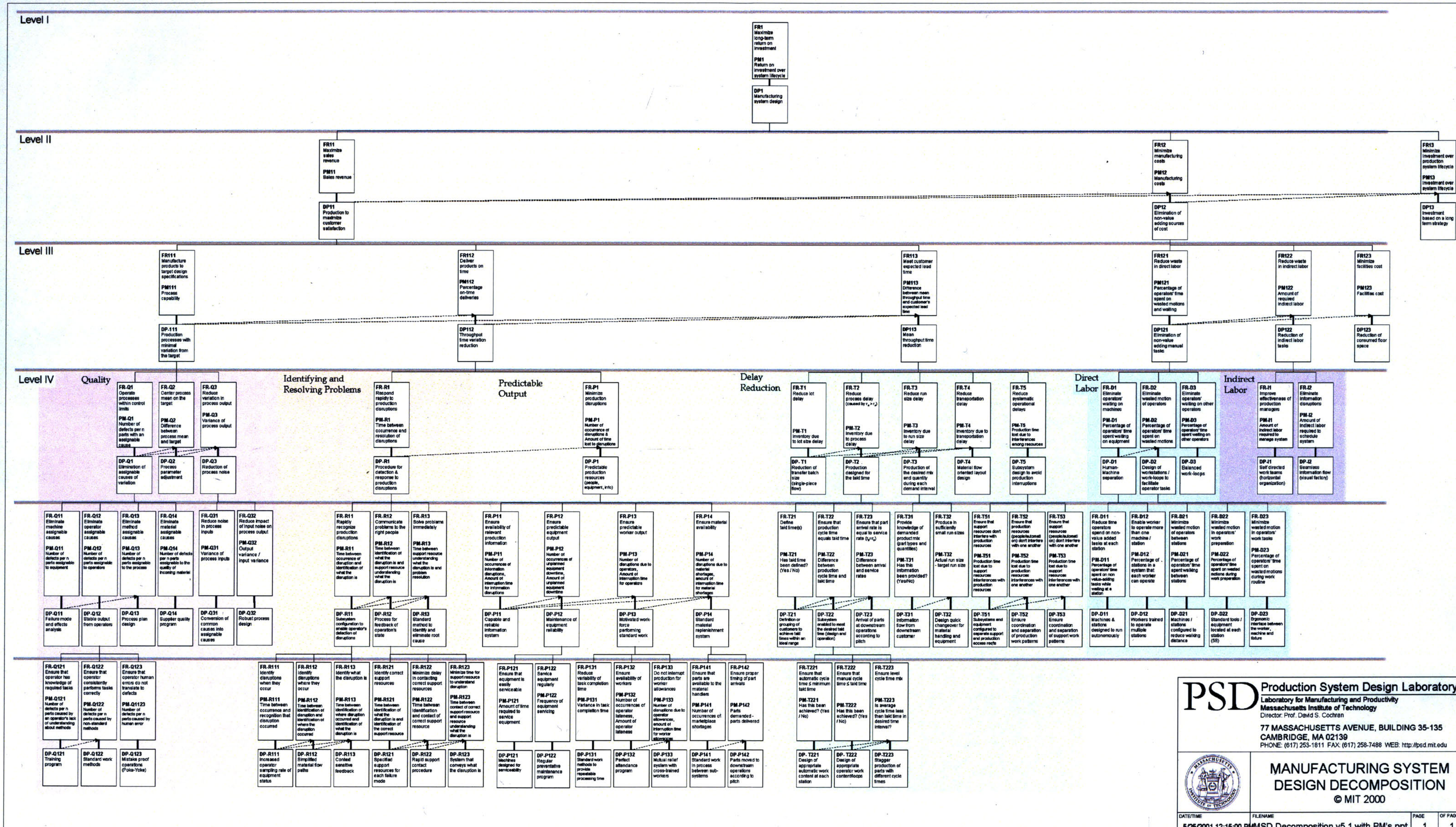
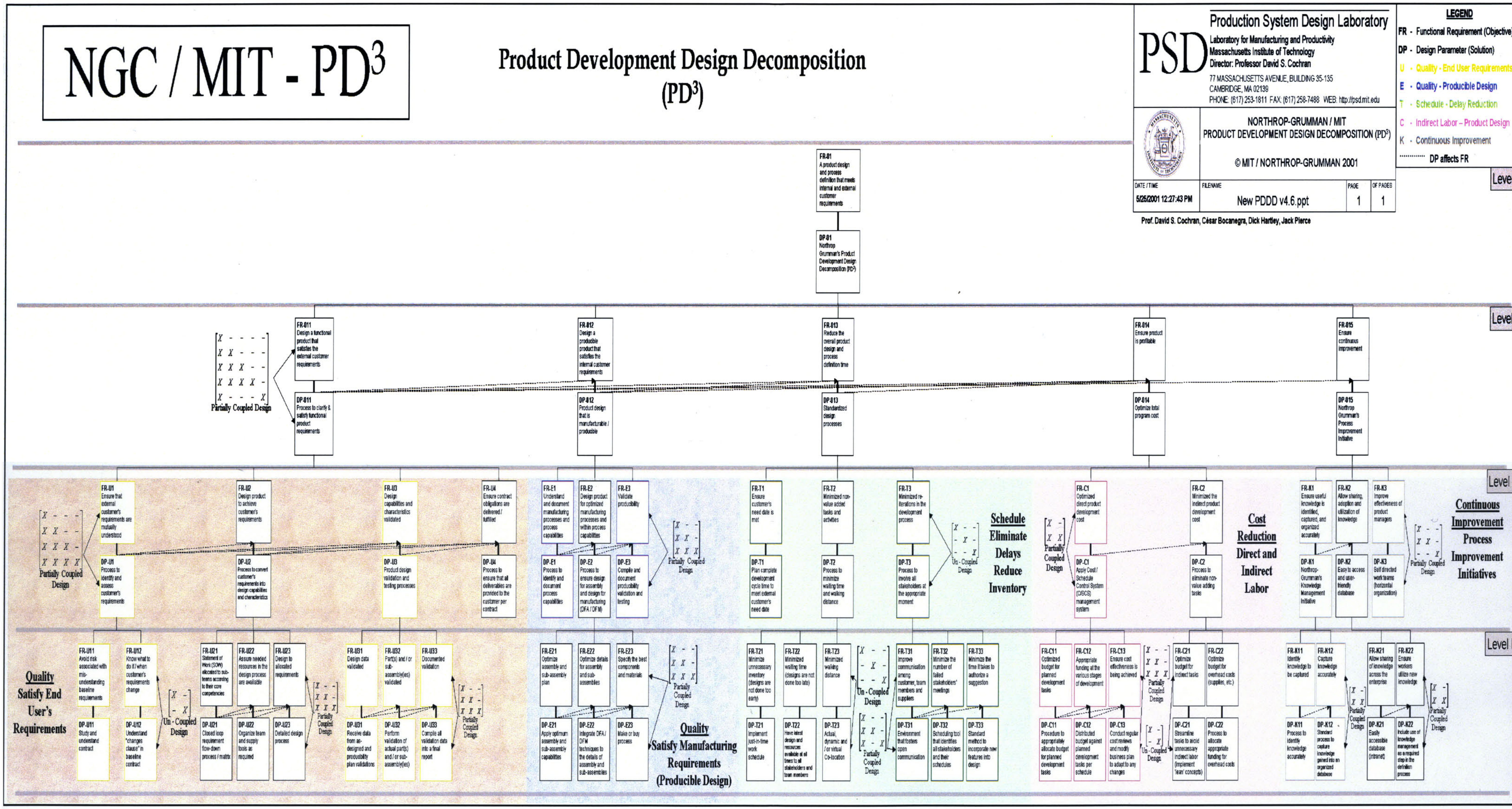
Appendix A

Manufacturing System Design Decomposition (MSDD)



Appendix B

Product Development Design Decomposition (PD3)



Appendix C

Design Matrix of the Product Development Design Decomposition (PD3)

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NORTHROP-GRUMMAN / MIT
PRODUCT DEVELOPMENT DESIGN DECOMPOSITION (PD^3)
DESIGN MATRIX

DATE / TIME	FILENAME	PAGE	OF PAGES
5/25/2001 11:45:33 AM	PDDD v4.6 Design Matrix.ppt	1	1

DP-01: Northrop Grumman's Product Development Design Decomposition (PD3)

- DP-011: Process to clarify & satisfy functional product requirements
  - DP-U1: Process to identify and assess customer's requirements (DP-U11, DP-U12)
  - DP-U2: Process to convert customer's requirements into design capabilities and characteristics (DP-U21, DP-U22, DP-U23)
  - DP-U3: Product design validation and testing processes (DP-U31, DP-U32, DP-U33)
  - DP-U4: Process to ensure that all deliverables are provided to the customer per contract
- DP-012: Product design that is manufacturable / producible
  - DP-E1: Process to identify and document process capabilities
  - DP-E2: Process to ensure design for assembly and design for manufacturing (DFA / DFM) (DP-E21, DP-E22, DP-E23)
  - DP-E3: Compile and document producibility validation and testing
- DP-013: Standardized design processes
  - DP-T1: Plan complete development cycle time to meet external customer's need date
  - DP-T2: Process to minimize waiting time and walking distance (DP-T21, DP-T22, DP-T23)
  - DP-T3: Process to involve all stakeholders at the appropriate moment (DP-T31, DP-T32, DP-T33)
- DP-014: Optimize total program cost
  - DP-C1: Apply Cost / Schedule Control System (C/SCS) management system (DP-C11, DP-C12, DP-C13)
  - DP-C2: Process to eliminate non-value adding tasks (DP-C21, DP-C22)
- DP-016: Northrop Grumman's Process Improvement Initiative
  - DP-K1: Northrop-Grumman's Knowledge Management Initiative (DP-K11, DP-K12)
  - DP-K2: Easy to access and user-friendly database (DP-K21, DP-K22)
  - DP-K3: Self directed work teams (horizontal organization)

FR-01: A product design and process definition that meets internal and external customer requirements

FR (level 1)	FR (level 2)	FR	DP-U11: Study and understand contract	DP-U12: Understand "changes clause" in baseline contract	DP-U21: Closed loop requirement flow-down process / matrix	DP-U22: Organize team and supply tools as required	DP-U23: Detailed design process	DP-U31: Receive data from as-designed and producibility plan validations	DP-U32: Perform validation of actual part(s) and / or sub-assembly(ies)	DP-U33: Compile all validation data into a final report	DP-U4	DP-E1	DP-E21: Apply optimum assembly and sub-assembly capabilities	DP-E22: Integrate DFA / DFM techniques to the details of assembly and sub-assemblies	DP-E23: Make or buy process	DP-E3	DP-T1	DP-T21: Implement just-in-time work schedule	DP-T22: Have latest design and resources available at all times to all stakeholders and team members	DP-T23: Actual, dynamic and / or virtual Co-location	DP-T31: Environment that fosters open communication	DP-T32: Scheduling tool that identifies all stakeholders and their schedules	DP-T33: Standard method to incorporate new features into design	DP-C11: Procedure to appropriately allocate budget for planned development tasks	DP-C12: Distributed budget against planned development tasks per schedule	DP-C13: Conduct regular cost reviews and modify business plan to adapt to any changes	DP-C21: Streamline tasks to avoid unnecessary indirect labor (implement 'lean' concepts)	DP-C22: Process to allocate appropriate funding for overhead costs	DP-K11: Process to identify knowledge accurately	DP-K12: Standard process to capture knowledge gained into an organized database	DP-K21: Easily accessible database (intranet)	DP-K22: Include use of knowledge management as a required step in the definition process	DP-K3
FR-011: Design a functional product that satisfies the external customer requirements	FR-U1: Ensure that external customer's requirements are mutually understood	FR-U11: Avoid risk associated with mis-understanding baseline requirements	X																														
		FR-U12: Know what to do if / when customer's requirements change		X																													
	FR-U2: Design product to achieve customer's requirements	FR-U21: Statement of Work (SOW) allocated to sub-teams according to their core competencies	X		X																												
		FR-U22: Assure needed resources in the design process are available	X			X																											
		FR-U23: Design to allocated requirements	X				X																										
	FR-U3: Design capabilities and characteristics validated	FR-U31: Design data validated			X	X	X	X																									
		FR-U32: Part(s) and / or sub-assembly(ies) validated			X	X	X		X																								
		FR-U33: Documented validation	X		X	X	X			X																							
	FR-U4: Ensure contract obligations are delivered / fulfilled		X	X	X	X	X	X	X	X	X																						
FR-012: Design a producible product that satisfies the internal customer requirements	FR-E1: Understand and document manufacturing processes and process capabilities					X	X	X	X			X																					
	FR-E2: Design product for optimized manufacturing processes and within process capabilities	FR-E21: Optimize assembly and sub-assembly plan	X		X	X	X	X	X			X	X																				
		FR-E22: Optimize details for assembly and sub-assemblies	X		X	X	X	X	X			X		X																			
		FR-E23: Specify the best components and materials	X		X	X	X					X			X																		
	FR-E3: Validate producibility					X	X	X	X		X	X	X	X	X	X																	
FR-013: Reduce the overall product design and process definition time	FR-T1: Ensure customer's need date is met		X	X	X	X	X	X	X	X	X		X	X	X	X	X																
	FR-T2: Minimized non-value added tasks and activities	FR-T21: Minimize unnecessary inventory (designs are not done too early)			X	X	X											X															
		FR-T22: Minimized waiting time (designs are not done too late)			X	X	X												X														
		FR-T23: Minimized walking distance				X														X													
	FR-T3: Minimized re-iterations in the development process	FR-T31: Improve communication among customer, team members and suppliers			X	X				X											X												
		FR-T32: Minimize the number of failed stakeholders' meetings				X														X		X											
		FR-T33: Minimize the time it takes to authorize a suggestion				X	X													X			X										
FR-014: Ensure product is profitable	FR-C1: Optimized direct product development cost	FR-C11: Optimized budget for planned development tasks	X		X								X	X	X		X	X		X			X	X									
		FR-C12: Appropriate funding at the various stages of development			X												X								X								
		FR-C13: Ensure cost effectiveness is being achieved				X	X		X				X	X	X			X				X	X			X							
	FR-C2: Minimized the indirect product development cost	FR-C21: Optimize budget for indirect tasks																		X						X	X						
		FR-C22: Optimize budget for overhead costs (supplies, etc.)																										X					
FR-015: Ensure continuous improvement	FR-K1: Ensure useful knowledge is identified, captured, and organized accurately	FR-K11: Identify knowledge to be captured				X				X		X				X						X							X				
		FR-K12: Capture knowledge accurately				X				X		X				X						X								X			
	FR-K2: Allow sharing, adoption and utilization of knowledge	FR-K21: Allow sharing of knowledge across the enterprise				X						X				X			X	X		X							X	X	X		
		FR-K22: Ensure workers utilize new knowledge										X										X								X		X	
	FR-K3: Improve effectiveness of product managers																														X	X	X