Accounting for System Level Interactions in Knowledge Management Initiatives

by

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Submitted to the System Design & Management Program
in Partial Fulfillment of the Requirements for the Degree of

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ABSTRACT

An overview of the operation of a modern, high bypass ratio, dual spool turbofan engine is presented to identify the multitude of system level interactions that must be considered when developing such an engine. The Design Structure Matrix (DSM) is used to demonstrate how it maps these relationships and, if utilized in the right manner, can reduce the occurrence of escapes (i.e., a deliverable that does not meet customers' expectations). The context of this thesis is the complex system design, and development process, of a commercial aircraft gas turbine engine (specifically the Pratt & Whitney PW4000 engine family).

Unlike previous gas turbine engine DSM work, the matrix created in this thesis is generated from the point of view of the Systems Engineering organizations at Pratt & Whitney. The sequenced matrix captures the non-local knowledge that is currently absent from Pratt & Whitney's existing knowledge management documentation. Testing the DSM against past instances of rework and unexpected design issues substantiates its validity as the basis for performing this function. Finally, examples are presented to demonstrate how the DSM can be used to prevent future escapes.

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I also learned a lot from fellow P&W employee and classmate, Douglas Hague, as we jointly prepared the DSM used in our theses. Doug's background in manufacturing and design integration enhanced my understanding of these business areas. Discussions with Doug and his thesis advisor, Steven Eppinger, added greatly to my learning experience.

The thesis work of P&W alumni of the System Design and Management (SDM) program deserves recognition, as it provided a foundation for my thesis work:

> Mascoli, Gregory J., "A Systems Engineering Approach to Aero Engine Development in a Highly Distributed Engineering and Manufacturing Environment." MS Thesis, Massachusetts Institute of Technology, 1999.
>
> Rowles, Craig M., "System Integration Analysis of a Large Commercial Aircraft Engine." MS Thesis, Massachusetts Institute of Technology, 1999.
>
> Glynn, Stephen V. and Pelland, Thomas, "Information Flow & Knowledge Capture Lessons for Distributed Integrated Product Teams." MS Thesis, Massachusetts Institute of Technology, 2000.
>
> Moy, Habs M., "Commercial Gas Turbine Platform Strategy and Design." MS Thesis, Massachusetts Institute of Technology, 2000.

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CHAPTER 1 – INTRODUCTION

1.1 STATEMENT OF PROBLEM

Employment in the United States aerospace industry dropped from approximately 1.3 million employees in 1989 to approximately 850,000 employees in 1999.[1] This huge decrease was predicated by the decline in government defense contracts as well as consolidation within the aerospace industry. This downsizing has eliminated many experienced engineers and technicians from the workforce, causing corporations to unknowingly sacrifice their core capabilities.[2]

In addition to the loss of technical experts, a large number of young engineers are choosing non-aerospace careers. Biotechnology, computers and software are the primary high technology fields attracting new engineers away from aerospace due to the promise of better pay. This is a large problem in retaining new engineers for more than a couple of years.[3]

The two dynamics discussed above have resulted in a non-uniform distribution of manpower experience. Employees with over 20 years experience make up the smallest segment while employees with less than 3 years experience comprise the largest segment.[4]

This dichotomy of experience has severely impacted the transfer of informal (tacit) knowledge from the technical experts to the new engineers that now dominate the workforce. Some feel that it is the lack of this informal knowledge that is missing in today's aerospace industry and contributing to its problems.[5] Perhaps, the most well publicized problem that can be attributed to such a lack of experience is the loss of NASA's Mars Climate Orbiter due to an

[1] William B. Scott, "'People' Issues Are Cracks In Aero Industry Foundation," Aviation Week & Space Technology, 21 June 1999, 63-66.
[2] William B. Scott, "Industry's 'Hire-and-Fire' Paradigm Is Obsolete," www.aviationweek.com/aviation/aw63-66b.htm, 21 June 1999.
[3] Ibid.
[4] Inferred from P&W internal data.

English-to-metrics unit conversion mistake.[6] Although, documented examples of these types of failures are rare, they probably occur more frequently than aerospace corporations would like to admit.

The transfer of this tacit knowledge is crucial to the success of organizations in today's "faster, better, cheaper" business environment. In a survey of knowledge management projects, it was discovered that most simply re-used structured knowledge, while very few developed knowledge transfer infrastructures to structure and map knowledge.[7]

1.2 THESIS GOAL

This thesis will attempt to show how the Design Structure Matrix (DSM) can be used to capture this informal knowledge and if applied in the right manner, reduce the occurrence of escapes such as the Mars observer incident mentioned above.

The context of this thesis will be the complex system design and development process of a commercial aircraft gas turbine engine (specifically the Pratt & Whitney PW4000 engine family). This product is a good candidate for such an exercise since changes in aircraft engines have been primarily evolutionary over the last 25 years.[8] A system level parameter DSM will be created and analyzed to capture the interactions between stakeholder needs and the parameters used to describe the engine at the system level. These relationships will be assessed against P&W's existing engineering knowledge management documentation, Standard Work, to determine its value in representing these interactions.

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[5] Ibid., idem, "Industry's 'Hire-and-Fire' Paradigm Is Obsolete."

[6] Anonymous, "Aerospace Executives: Do They 'Get It' Yet," Aviation Week and Space Technology, 15 November 1999, 130.

1.3 RELATED WORK

The research in this thesis builds off the work of Gregory Mascoli, who developed a parameter DSM to help identify groupings among the product development organization at Pratt & Whitney.[9] Mascoli's research was more focused on the parameters used during the preliminary design phase while the DSM used in this thesis focuses on derivative design changes. Additionally, although the DSM contained some system level parameters, the majority are module specific parameters. The conclusions from this thesis should apply to both matrices.

This thesis also continues the study of P&W's knowledge management strategy initiated by Stephen Glynn and Thomas Pelland.[10] They analyzed the DSM's created by Mascoli and Craig Rowles (see below) to better understand the information flow within P&W's distributed engineering environment. They recognized the need for developing a standard methodology for capturing component and system integration issues and the value of the DSM in facilitating such a task.

The DSM created in this thesis will also be compared against the modified Quality Function Deployment (QFD) analysis performed by Habs Moy on the PW4000 family of engines[11] and the DSM's (component and team) created by Craig Rowles in his system integration analysis of the PW4098 engine.[12]

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[7] Don Cohen, Managing Knowledge In The New Economy (Chicago: Conference on Organizational Learning, 1998), 19-20, 1222-98-CH.
[8] Jack L. Kerrebrock, Aircraft Engines and Gas Turbines (Cambridge: MIT Press, 1996), ix.
[9] Gregory J. Mascoli, "A Systems Engineering Approach to Aero Engine Development in a Highly Distributed Engineering and Manufacturing Environment," (MS Thesis, Massachusetts Institute of Technology, 1999).
[10] Stephen G. Glynn, and Thomas Pelland, "Information Flow & Knowledge Capture Lessons for Distributed Integrated Product Teams," (MS Thesis, Massachusetts Institute of Technology, 2000).
[11] Habs M. Moy, "Commercial Gas Turbine Engine Platform Strategy and Design," (MS Thesis, Massachusetts Institute of Technology, 2000).
[12] Craig M. Rowles, "System Integration Analysis of a Large Commercial Aircraft Engine," (MS Thesis, Massachusetts Institute of Technology, 1999).

The prime difference between the DSM in this thesis, and the prior gas turbine engine DSM work, is that it is created from the point of view of the Systems Engineering organization at Pratt & Whitney. The perspective of the other DSM's was at the lower component or module level of the gas turbine engine. The development of the parameters and their interactions for the DSM in this thesis was done in cooperation with Douglas Hague.[13]

[13] Douglas C. Hague, "Description of a Turbofan Engine Product Development Process," (MS Thesis, Massachusetts Institute of Technology, 2001).

CHAPTER 2 – BACKGROUND

2.1 COMMERCIAL AIRCRAFT GAS TURBINE ENGINE FUNDAMENTALS

The purpose of an aircraft gas turbine engine is to generate a propulsive force greater than the associated drag forces operating on the aircraft. There are many configurations of gas turbine engines used for aircraft applications: turbojets, turbofans, turboprops and turboshafts. The subject of this thesis is the high bypass ratio, dual spool turbofan. An example of such an engine is the PW4000 family of engines, one of which is depicted in Figure 2.1:

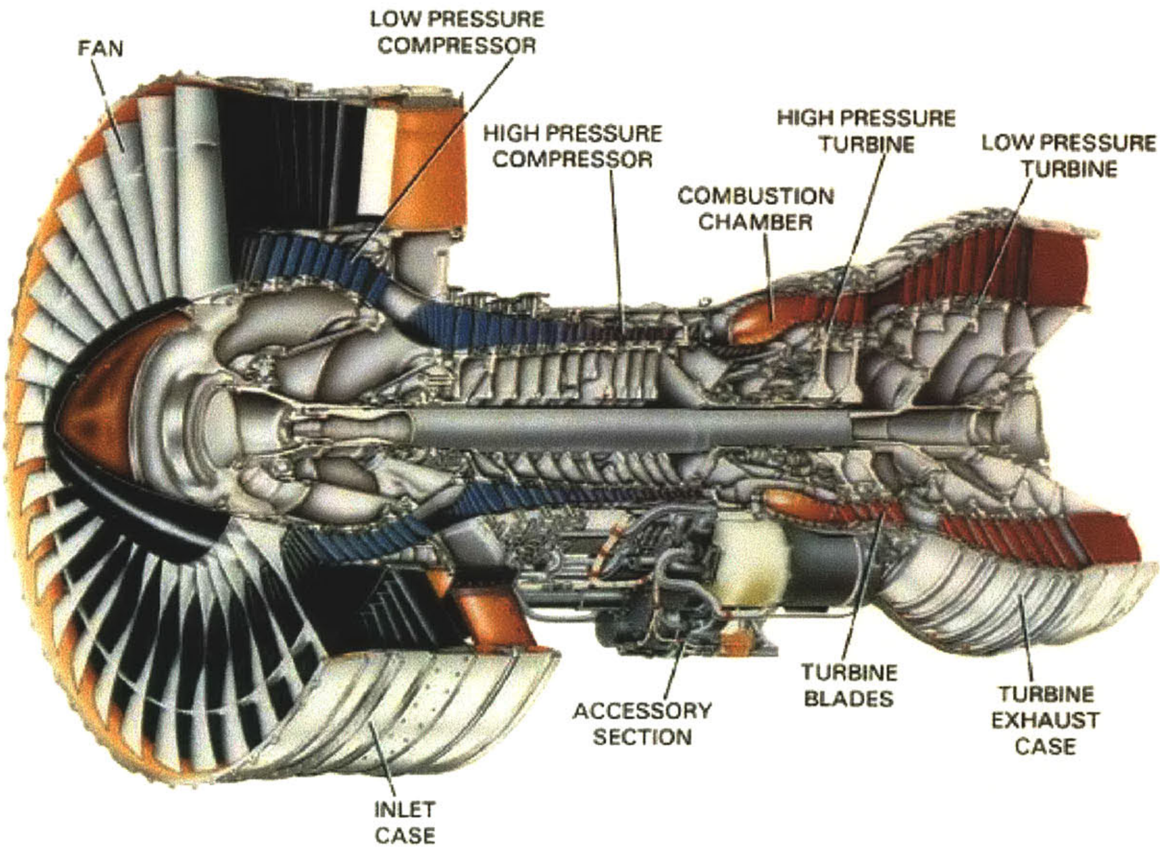

Figure 2.1 Modern, High Bypass Ratio, Dual Spool Turbofan: PW4000 (94 inch) Fan Engine.[14]

[14] http://pwww.eh.pweh.com/communications/aboutengines/gallery/lg_pw4000_94cut.html

The following overview of the components and operation of a turbofan engine is comprised of information taken from a P&W educational manual[15] and notes from the MIT graduate engineering course, "Aircraft Engines and Gas Turbines", offered in the fall 2000 semester.[16] The section is intended to make the reader aware of the system level trades that must be considered when designing, developing and supporting such an engine to meet customer requirements while also maximizing value to the company and its shareholders. The customer in the aircraft engine industry takes many forms: airlines, airframers and certification authorities. A good engine will optimize fuel consumption, weight, environmental impact, manufacturing cost, maintenance cost and reliability for the given aircraft and mission.

These engine requirements are set by the aircraft mission analysis (i.e., aircraft size, range, flight profile, intended operations, etc.). The critical conditions for the engine are take-off, climb, cruise and engine-out conditions. The range of the aircraft is a function of the aerodynamics and weight of the aircraft as well as the overall propulsion system efficiency. Fuel consumption (measure of system efficiency) at climb sets the range for short-haul aircraft while fuel consumption at cruise set the range for long-distance aircraft. The required thrust at take-off and engine-out conditions is driven by the maneuverability requirements of the aircraft.

Relative to the aircraft aerodynamics, the inlet is normally not considered to be part of the engine, but rather, part of the airframe. The inlet directs the outside air to the face of the compression system: the fan. Since the inlet is delivering air to the compression system, it must do so with as little pressure variation (distortion) and turbulence as possible. It must also attempt to recover as much of the free airstream total pressure as possible. In addition to these engine concerns, the airframer desires that the inlet have minimum drag (air resistance).

[15] Anonymous, The Aircraft Gas Turbine Engine And Its Operation, (Pratt &Whitney Part No. P&W 182408, 1988).
[16] Alan H. Epstein, MIT Course 16.511, Aircraft Engines and Gas Turbines, Fall 2000.

The engine fan is located to the rear of the engine inlet. It comprises one stage of rotating blades and one stage of stationary vanes. Braces (part span shrouds) are sometimes used between the fan blades to prevent vibratory flutter. These shrouds can be seen in Figure 2.1. Part span shrouds are not needed on fan blades with long chords (distance from leading edge to trailing edge) since these blades are more aerodynamically efficient.

The fan is the first stage of the compression system that will be explained in more detail below. As the air leaves the fan, it is separated into two streams. The smaller stream that passes through the basic engine is called the primary airstream. The larger stream that only passes through the fan ducts is called the secondary airstream. The weight ratio of secondary air to primary air is called the engine bypass ratio. The higher the bypass ratio, the greater the thrust and fuel efficiency. Perhaps most importantly, the greater the bypass ratio, the lower the noise. The high bypass ratio turbofan has proven to be the most effective engine architecture for reducing engine noise due to the reduction of fan exit air velocities. The noise reduction brought about by these high bypass ratio engines dominates the noise suppression that can be attained from acoustic liners or nozzle flow mixers. However, the benefits of increased bypass ratio come at the price of increased weight, drag and cost.

The purpose of the compression system is to raise the pressure and temperature of the primary airstream prior to the combustion process. The combustion of fuel and air at normal atmospheric conditions will not produce enough energy from the expanding gases to generate useful work at reasonable efficiencies. In order to improve the efficiency of the combustion process, high-pressure air is required.

Compression in a PW4000 type engine is achieved by dual axial compressors: the low-pressure compressor and high-pressure compressor. The high-pressure compressor has shorter blades than the low-pressure compressor and is lighter in weight. The air in an axial compressor flows in an axial direction through a series of rotating "rotor" blades and stationary "stator" vanes that are concentric with the axis of rotation. The flow path of an axial compressor decreases in cross-sectional area in the direction of flow. This results in decreased volume and increased pressure and temperature as compression progresses from one stage to the next. Since compression is forcing the air to move against an adverse pressure gradient, compressors require more stages than turbines. Additionally, because of this gradient, airflow through the compressor is highly unstable.

The design of a compressor stage to achieve the required pressure rise must also consider the following factors: vibration, centrifugal forces, aerodynamic loading and the cascade effect. The cascade effect is the phenomenon of air separating from the trailing edge of one blade being impacted by the leading edge of the following blade. The blade geometry, spacing of the blades and the clearance of the rotating blades to the outer case are influenced by all of these concerns.

The objective of the overall compressor design is to achieve the desired efficiency while maintaining acceptable surge margin, weight and cost. Surge is a disturbance of the airflow through the compressor. It can be caused by a number of factors (deterioration, distortion, power changes, Reynolds number effects, water/ice ingestion, etc.). In a surge, the compressor blades lose lift; similar to an airplane wing when it stalls. Surge usually results in a loss of power for only a fraction of second. They are characterized by a loud bang and a puff of smoke and can sometimes damage an engine. Compressor surge has been likened to a car engine's backfire.[17] Achieving the optimum balance between efficiency and surge margin is obtained by

[17] Some of this definition of compressor surge has been acquired from http://www.pratt-whitney.com/engines/terminology.html

proper selection of flow area, number of stages, compressor length and tip clearance.[18] The core efficiency is set by the compression pressure ratio that is currently limited by material limitations at the compressor exit temperature. The pressure ratio at a given flow across a compressor is known as the operating point of a compressor. The locus of operating points is known as the operating line of the compressor.

The threats to cause engine surge are different for the low-pressure and high-pressure compressor. The low-pressure compressor is more sensitive to deceleration transients while the high-pressure compressor is sensitive to acceleration transients. Different threats for each compressor also exist depending on flight condition and power setting.

The rotational speed of the high rotor (N2) is set by high-pressure turbine stress limits while the rotational speed of the low rotor (N1) is set by the fan tip speed required to attain acceptable fan surge margin and loading.[19] By having two mechanically independent rotor systems, the compression system has more flexibility to handle part-throttle and starting conditions without producing a compressor surge. In other words, each compressor is allowed to operate closer to its design point during these lower power conditions than would be possible with a singe axial compressor. By operating at independent speeds, the compression ratio can be increased without decreasing efficiency. The high-pressure compressor runs at higher speeds than the low-pressure compressor. The stall margin and pressure rise can be increased with rim speed but the disk weight will also have to increase (i.e., stronger materials) to ensure the disk is still capable of meeting its low cycle fatigue requirements.

However, dual spools are not enough to meet today's efficiency and surge margin goals. In order to keep the tip clearance between the compressor blades and case as small as possible, a

[18] "Flowpath Analysis", Unpublished, June 2000.
[19] Ibid.

combination of abradable and abrasive materials are used. Compressor blades with abradable tips will ensure that as the blades expand with heat, the tips will grind away and establish their own clearances. Another option is to make the airseals on the compressor case abradable and use an abrasive material for the compressor blade tips. In this scenario, the airseal will rub away as the compressor stage sets its own clearances.

While maintaining tight clearances helps reduce boundary layer losses and improves surge margin, two other methods are employed on the PW4000 to minimize the tendency of the engine to stall. One is the use of stability bleed valves while the other is the use of variable stator vanes.

Stability bleed valves are located at the exit of the low-pressure compressor (2.5 bleed) and the middle of the high-pressure compressor (starting and stability bleed). The low compressor bleed is a modulated, butterfly valve while the high compressor bleeds are poppet, on/off valves. These valves, when open, direct part of the primary airstream overboard. These bleed valves can "unload" the compressor during certain operating conditions to reduce the pressure ratio across the compressor for a given airflow. These bleeds are controlled by the Electronic Engine Control (EEC) and are typically opened at low power, and closed at high power to minimize their impact on cycle performance. The EEC will be described in more detail below.

Variable stator vanes refer to the first four stages of compressor stators in the high-pressure compressor, whose mounting angles can be varied with changing conditions. The EEC also controls the angles of the stator vanes. During starting and low power, the vane angles are partially closed to reduce the amount of airflow entering the compressor. As the engine power increases, and the engine approaches its design operating point, the vane angles open up to allow more airflow.

As the primary airstream leaves the axial compressor, it passes through compressor exit guide vanes to reduce some of the swirl of the air before it enters the diffuser. The coatings and cooling schemes used in the turbines cannot be used in the compressor exit stages due to aerodynamic, weight and cost concerns. The compressor exit temperature is currently limited by material properties. The diffuser has an expanding internal diameter to decrease the velocity and increase the static pressure of the air prior to entering the combustor.

Fuel is introduced into the airstream at the front of the combustor in a spray form that is suitable for rapid mixing with air for combustion. The fuel is atomized, vaporized, and then mixed in the gaseous phase where is reacts at near stoichiometric conditions. The fuel is carried from outside the engine by a manifold system to injectors mounted in the burner. (The terms, burner and combustor are used interchangeably). The ignition system provides a high-energy spark to ignite the fuel-air mixture being sprayed into the combustion chamber. The ignition system consists of an electrical power source, two igniter plugs, separate exciters for each plug and the associated wiring harnesses and high tension leads. The EEC controls the engine power conditions where the ignition system is activated.

The combustor burns a mixture of fuel and air, and delivers the resulting gases to the turbine at a temperature distribution that will not exceed the allowable limit at the turbine inlet. Maximizing the turbine inlet temperature results in more power and better fuel consumption. However, as will be shown in the discussion of turbines, accommodating these temperatures is a complex task. The technology to handle these temperatures currently limits the turbine inlet temperature of the engine.

The burner must add enough energy to the primary gaspath to accelerate its mass enough to produce the desired power for the turbine and thrust for the engine. Other constraints of good burner design include minimizing the pressure loss of the primary gaspath, maximizing the combustion efficiency, and maintaining acceptable flame stability. Flame stability includes having a low risk of blowout and ensuring that no burning occurs after the gases leave the burner exit. In addition to these classical requirements, the emissions (nitrous oxides, carbon monoxide and unburned hydrocarbons) and visible smoke are perhaps the most important burner measures due to today's stringent environmental regulations.

The height and length of the burner are set by the combustion stability and efficiency requirements.[20] Production of nitrous oxides is a strong function of high local gas temperatures and time spent at temperature. The production of carbon monoxide and unburned hydrocarbons are the emissions concern at low power due to less than desired combustion efficiency. In order to minimize the generation of nitrous oxides, combustor design attempts to avoid high local gas temperatures, oxygen rich combustion areas and long residence time at high temperatures. The generation of carbon monoxides and unburned hydrocarbons is avoided by minimizing efficiency losses at low power. Controlling the fuel/air mixture at the fuel injectors reduces smoke (caused by incomplete combustion). These low emissions features come at the price of increased weight, complexity and cost.[21]

The turbines in all modern jet engines are axial flow devices. The turbines consist of one or more stages located immediately to the rear of the burner section. For dual compressors, dual turbines are also required. The turbines extract kinetic energy from the expanding gases from the burner. This energy is then converted into shaft horsepower to drive the compressors and engine accessories. The forward part of the turbine, the high-pressure turbine that drives the high-pressure compressor, has fewer stages than the low-pressure turbine since it receives the

[20] Ibid.
[21] "Systems Engineering Approach To Cycle And Configuration Selection", Unpublished, June 2000.

gasflow directly from the burner. The low-pressure turbine, located in the rear of the engine, receives less energetic gases, so it requires more stages to extract the remaining power. A turbine stage consists of a stationary vane row (stator) followed by a rotating blade row (rotor). These components must operate in a high temperature environment while maintaining efficiency and durability.

In order to operate at peak efficiency, losses due to airfoil surface and endwall friction, cooling flow mixing, tip and internal leakage and shocks must be minimized. Endwall losses have been minimized by the use of three-dimensional design techniques. The clearance between the rotating blades and the outer case is controlled by the turbine case cooling (TCC) system that scoops air from the fan (secondary) stream and distributes it through ducts to spray over the turbine cases. The air causes the hot cases to shrink, and reduces the gap around the rotating blades. This reduced gap results in improved fuel efficiency. The EEC controls the TCC system. In addition to being used to control the diameter of the turbine case, air from the fan stream is also used to cool the external components in the core compartment of the engine nacelle. The EEC also controls the flow of this air through the Nacelle Air Cooling (NAC) valve.

In order to be durable, turbines must simultaneously handle both high speeds and high temperatures. This environment makes creep (time and temperature dependent deformation), fatigue (material weakening due to cyclic loading), and sulfidation (corrosion due to the condensation of sodium sulfate on the surface of a material) the primary threats to the durability of a turbine blade. The use of single crystal materials and thermal coatings help the turbines withstand this high temperature environment. The use of coatings brings about some inherent problems of thermal expansion mismatch, chemical compatibility between the metal and the coating, and spallation. Thermal relief is also provided by directing compressor bleed air through passages inside the engine to the turbine area where the air (coolant) is led to longitudinal holes in the vanes and blades. Cooling is generally only required in the front stages of the turbine since the temperature of the primary gaspath decreases as it travels toward the exit of the engine. The EEC also schedules the turbine cooling airflow (TCA). The airflow is turned off at low power conditions in order to minimize the efficiency penalty on the cycle.

The turbine design features discussed above allow the turbines to attain their efficiency and durability goals but also come at the expense of increased cost, weight and complexity. The turbine cooling schemes (TCC and TCA) additionally result in overall cycle efficiency losses. As turbine temperatures continue to increase in the pursuit of increased specific power, better materials and cooling schemes will be required in the turbine design.

An exhaust duct (tailpipe and nozzle) is added to collect and straighten the primary gasflow as it comes from the turbine and to increase the velocity of the gases before they are discharged from the exhaust nozzle at the rear of the duct. Increasing the velocity of the gases increases their momentum, which results in more thrust. The struts located in the engine ducting support the rear bearing of the engine and also house the exhaust gas temperature and pressure probes used by the EEC.

The engine thrust reverser that directs the secondary airstream at a forward angle to slow the aircraft after it touches the ground on landing complicates the exhaust duct of the fan stream. Reversers have to be strong, relatively light in weight, and reliable. They have to be able to produce at least 40% of the full forward thrust in reverse. When not in use, the reverser has to be streamlined into the engine nacelle so that it does not add appreciably to the frontal area of the engine.

Accessories for gas turbine engines, other than the thrust reverser, can be divided into two categories: those driven by bleed air taken from the compressor section of the engine, and those driven mechanically by an accessory drive shaft and gear shaft connected to the turbine shaft. Most of the airbleed driven accessories (low pressure compressor 2.5 bleed, high-pressure compressor starting and stability bleed and turbine cooling air) were discussed above. Additional airbleed driven accessories include air bled from the mid and rear stages of the compressor to drive the aircraft air conditioning system and the aircraft/inlet anti-icing system. Air from the high-pressure compressor is also used to cool the bearing compartments and control the thrust bearing loads. As with all bleeds, the power extraction is obtained only at a sacrifice in engine output and fuel consumption.

The main gearbox on modern high bypass ratio, dual spool turbofan is mounted within the engine core cowl and driven by an angle gearbox through a towershaft from the high-pressure compressor. The gearbox drives the fuel pump, oil scavenge pump, high rotor tachometer, electrical generator for the EEC, hydraulic pump and the integrated drive generator for aircraft electricity. The gearbox also provides inputs for the air-turbine starter, and also houses the oil filter, metal chip detectors and the oil pressure-regulating valve.

The oil system provides pressurized oil to lubricate, cool, and clean the engine main bearings, gearbox gear trains, and accessory drives of a jet engine. The lubrication method most generally used is known as a calibrated system, since each bearing has its oil specifically controlled by a calibrated orifice that provides the proper oil flow at all engine speeds. Oil from the tank (or returned from the scavenge pumps) is delivered into an oil boost pump. From the boost pump, the oil is fed through the main oil filter. If the filter should become clogged, a bypass valve will open and permit unrestricted flow to the bearings. Ports at filter inlet and exit allow the filter pressure drop to be monitored for clogging. A pressure relief valve sends excess oil back to the tank. From the main oil filter, the oil passes to the air-oil heat exchanger where the oil is cooled by air from the fan stream (or 2.5 bleed discharge). The EEC also controls the valve controlling the amount of air and oil entering the heat exchanger. After the heat exchanger, the oil passes through "last chance" strainer before going to the main bearing compartments. Each bearing compartment has its own scavenge pump to send oil back to the tank. The oil from the scavenge pump is deaerated prior to being re-used.

This description of the PW4000 engine has included many references to the Electronic Engine Control. The basic purpose of the EEC is to reduce the workload of the flight crew. In addition to the control of the valves mentioned above, the EEC establishes power settings for all engine operating conditions. It does so by controlling fuel scheduling and heating. Fuel flows from the aircraft fuel tank to the boost stage of the engine fuel pump that carries fuel to the fuel oil cooler. This heat exchanger de-ices the fuel before it enters the fuel filter. The fuel is filtered, sent to the main stage of the fuel pump, and flows to the fuel-metering unit. The fuel-metering unit responds to commands from the control. The metered fuel for the engine combustor flows through the fuel flow transmitter to the fuel distribution valve, and bypass fuel is returned to the pump. The metered fuel flows through the manifolds to the fuel injectors.

The aim of this section was to convey that the design of a modern, high bypass ratio, dual spool turbofan is started by and constrained by an identified need. There may be many possible solutions but none can be identified as unique or optimum. The final solution always involves judgement and compromise. The process of arriving at this solution is inherently iterative. It requires returning to earlier steps when prior assumptions are found to be invalid. The design of such a complex system requires active participation and disciplined communication by all of the representatives from the various technical specialties. Since each part of the system influences all the others, the best solutions can be arrived at only if the participants share their findings clearly and regularly.[22]

2.2 PRODUCT DEVELOPMENT ORGANIZATION AT PRATT & WHITNEY

The intent of this section is to provide the reader with a sense of the rapid changes that have occurred within the technical organization of Pratt & Whitney, specifically in the large commercial engine business, over the last 10 years.

Pratt & Whitney is a leader in the design, manufacture and support of engines for commercial, military and general aviation aircraft, and space propulsion systems. Pratt & Whitney is a division of United Technologies, a $24.1 billion company that includes Otis elevators and escalators, Carrier heating and air conditioning systems, Sikorsky helicopters and Hamilton Sundstrand aerospace systems. Pratt & Whitney is celebrating its 75th anniversary in 2000. Sales for P&W in 1999 were $7.67 billion.

Pratt & Whitney has approximately 30,000 worldwide employees. P&W's five business units are headquartered in three locations: Large Commercial Engines and Engine Services in East Hartford, CT; Large Military Engines and Space Propulsion in West Palm Beach, FL; and Small Commercial Engines in Longueuil, Quebec.[23]

The engineering department for both Large Commercial and Large Military engines comprises about 5000 people.[24] Manufacturing is split among the five following sites: Middletown, CT; East Hartford, CT; North Haven, CT; North Berwick, ME; and Columbus, GA.

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[22] Jack D. Mattingly Wlliam H. Heiser, Daniel H. Daley, Aircraft Engine Design, (Washington D.C.: American Institute of Aeronautics and Astronautics, Inc., 1987), 3-4.
[23] http://www.pw.utc.com/
[24] Paul B. Greenberg, "Pratt & Whitney Evolution of Technical Organization", Unpublished, October 1999, 2.

More than 600 airlines operate with Pratt & Whitney large commercial engines in more than 150 countries.[25] P&W powers nearly 75% of the world's commercial aircraft.[26]

Prior to 1990, P&W was a classic functional organization with engineering, manufacturing, and customer support regarded as separate entities. The development process was also serial in nature with engine certification requiring approximately 5 years. During the 1990's both the organization and the development process have gone through many changes. Today, the engineering population has been reduced by roughly half of the level it had in 1990. The number of concurrent development programs has increased by a factor of 4 and engine certification times have dropped to less than 3 years.[27]

These changes started with the advent of Integrated Product Deployment (IPD) in June 1990; a cross-functional product design and development methodology. After the deployment of IPD, the next change (in 1991) was to co-locate all engineers working on the next development program, the PW4084. In 1993, the concept of co-location was extended with the formation of Component Centers. These centers, organized by program, were cross-functional teams with manufacturing and customer support representation. The desire to build closer ties with manufacturing and engineering resulted in the formation of Product Centers in 1995 which co-located engineers at the manufacturing sites. While Component Centers and Product Centers allowed manufacturing to be closer contact with the IPT's, their formation resulted in a loss of discipline capability with time.

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[25] http://www.pw.utc.com/
[26] Greenberg. 3.
[27] Ibid., 5-8.

The loss of discipline capability was corrected by establishing the System Engineering organization in 1997. This organization re-united engineering and provided a method to manage distributed engineering. The Systems Engineering organization was divided into 3 parts[28]:

Propulsion Systems Analysis (PSA) – identifies requirements, develops methods and systems, and ensures conformance to performance and operability criteria for all Pratt & Whitney propulsion systems, controls, and components.

System Design & Component Integration (SD&CI) – responsible for ensuring that technical execution and integration optimizes the engine design.

Product Development and Validation (PD&V) – plans and executes activities required to verify the performance and durability of the product.

As a whole, the Systems Engineering organization is responsible for the technical side of product development and field service. The organization manages interactions between components and the trades between different parameters. While component groups are interested in local optimization, the Systems Engineering organization always has to be cognizant of the customer needs and requirements of the engine. What's good for one component may not be good for the entire engine. A more detailed breakdown of how the Systems Engineering organization achieves this goal is discussed below.

PSA is responsible for ensuring that the system level parameters meet requirements. PSA also owns the aero-thermal simulations and the software used in the Electronic Engine Control. SD&CI owns the requirements and configuration of the engine. Functionally, SD&CI is also responsible for the secondary flow system and structural concerns such as fan blade out loads and vibration. PD&V is responsible for assembling, testing and certifying the engine. PD&V also develops and maintains the Engine Development Plan to ensure consistency with the overall

[28] The following definitions were obtained from the internal P&W website: http://pwww.eh.pweh.com/human-resources/develop/referenc/ppe_ref/mainmenuandglossary/default.htm

schedule and resource limitations of the program. PD&V is the largest organization in terms of number of people while SD&CI is the smallest.

While Product Centers co-located engineering and manufacturing; and Systems Engineering co-located program management with the systems engineers; the link between the Component Integrated Product Teams (CIPT's) and the programs was still missing. This was corrected in 1999, with the creation of five Module Centers, according to engine sections (except the Engine Center)[29]. These centers located the CIPT's at the Module Centers. Each Module Center is responsible for the design, development, production, assembly, and support of Pratt & Whitney's products.

Engine Center – where all the engine components are assembled and validated.

Electronic & Mechanical Systems Module Center – responsible for control systems, fuel systems, hydraulic systems, external lubrication systems, pneumatic systems, electronic sensing systems, and external architecture.

Compression System Module Center – responsible for the fan, low-pressure compressor, and high-pressure compressor.

Combustor, Augmentor & Nozzle Module Center – responsible for the combustor, augmentor (military applications) and nozzles.

Turbine Module Center – responsible for cooled blades, cooled vanes, shrouded blades, and turbine systems.

The relationship among teams in today's IPD structure is shown in Figure 2.2.

The Executive Council (EC) is the executive steering company made up of the company president and the company's top managers.

The Integrated Program Management Team (IPMT) is the highest level of management support for an engine program. The IPMT is comprised of leadership from the following functional areas: customer support, sales and marketing, finance, systems engineering, and the module centers. The IPMT is responsible for ensuring that the CIPT's meet the program requirements. The IPMT has the authority to make decisions relative to the direction, scope, allocation of budget, establishment of goals, and approval of configuration changes. Model Integrated Program Teams (MIPT's) have the same functional constituents as the IPMT but they are formed to focus on one particular engine model.

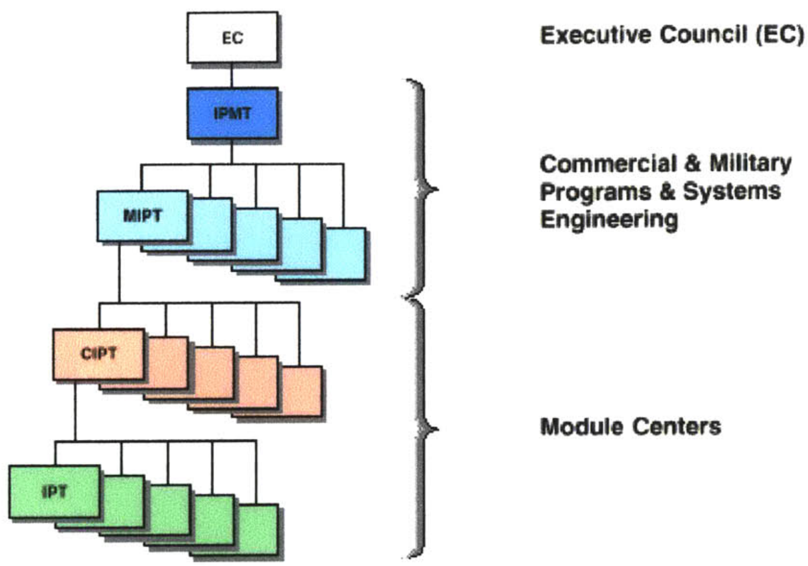

Figure 2.2 Integrated Program Deployment (IPD) Team Relationships[30]

The CIPT is a work team that produces a particular component of the engine. The CIPT as a delegate of the IPMT, will have the authority and responsibility for ensuring the Integrated Product Teams (IPT's) meet the component and systems level requirements for cost, schedule, quality, and performance.

The IPT's are established by the CIPT for any significant task within a program. These teams are responsible for integrating and documenting the design, manufacture, validation, and

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[29] Ibid.
[30] Figure 2.2 and the related organizational information is developed from the unpublished "Operating Guidelines for Integrated Program Deployment at Pratt & Whitney", Pratt & Whitney", November 10, 2000.

support elements of the products they deliver. The IPT is the working level team that solves part level problems and creates the product definition.

For more information on the IPD organization of Pratt & Whitney, the reader is advised to consult the Glynn and Pelland thesis.[31]

Due to the distributed engineering environment of the Module Centers, Discipline Chiefs were established to help P&W become more of a learning organization. Chiefs were assigned in each of the following disciplines: design, drafting, structures, secondary flow and heat transfer, project, manufacturing, aerodynamics, validation and quality. The charter of the Discipline Chiefs is to define, teach, check and improve Standard Work (P&W's engineering knowledge management documentation). The next section will contain a closer examination of the benefits and challenges of Standard Work.

The Discipline Chiefs are a "supply-based approach" to knowledge management that unfortunately has not shown to be a positive one. [32] With this approach, the responsibility for making the knowledge accessible is placed in the hands of those who actually create or gather the knowledge. A "demand-based approach" seems to be more productive. With this approach, the users of knowledge are encouraged to work in process teams that assume the full responsibility for the codification and dispersion of knowledge. Since the users of the knowledge are involved, they have a special interest in making sure it is available and up to date. Chapter 4 will attempt to show how the DSM can be used to institute more of a "demand-based approach" to knowledge management at Pratt & Whitney.

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[31] Glynn and Pelland, 30-40.

2.3 KNOWLEDGE MANAGEMENT AT PRATT & WHITNEY

As mentioned in the previous section, Standard Work is P&W's engineering knowledge management documentation. The official definition of Standard Work is:

> A disciplined approach to achieve business process effectiveness, efficiency, and agility. It is a method for capturing both process and product knowledge. It relates the best process approach developed to data and accesses historic levels of performance (capability) to frame the expected results. It is a series of activities that takes an input, adds value to it, and produces an output and is definable, predictable, and repeatable.[33]

Standard Work is one of the 10 elements of ACE (Achieving Competitive Excellence)[34]. ACE is a defined process for continuous improvement that provides the framework for each business unit to achieve a level of quality and productivity improvement that meets both internal and external requirements. The other elements of ACE are:

6S/Visual Workplace – safety, sort, straighten, shine, standardize and sustain.

Total Productive Maintenance – maintaining machines and equipment to get the most value and productivity.

Quality Clinic Process Chart – simple tool to identify process deficiencies.

Process Certification/Management – managing processes to reduce variation.

Mistake Proofing – using devices that prevent inadvertent human error.

Setup Reduction – reducing the time it takes to change over a machine or process.

Root Cause Analysis – rapid and persistent pursuit of fundamental breakdown, or failure of process, that when resolved prevents reoccurrence of the problem.

Market Feedback Analysis – using market data to improve product quality.

Passport System – holding effective program reviews to improve product quality.

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[32] Rene Tissen, Daniel Andriessen, Frank Lekanne Deprez, Value-Based Knowledge Management, (Amsterdam: Addison Wesley Longman Nederland BV, 1998), 187.
[33] Anonymous, "Standard Work – Overview For IPD", United Technologies Corporation, 1999.
[34] The following information on ACE is developed from http://pwww.eh.pweh.com/groups-and-events/groups/ace/

ACE was initially applied to the manufacturing setting. It was the foundation for lean production that sought to expose the hidden waste that exists between transforming raw material to the finished product. Lean production strives to ensure that manufacturing occurs the most economically (i.e., that the product is sold when it is needed and in the desired amounts).

The purpose of ACE is to standardize improvement practices under one umbrella. It has been instituted to improve the competitive advantage of the corporation by:

Reducing cost and lead times.
Increasing plant capacity, inventory turns, and reliability.
Empowering the workforce to focus on quality, productivity, and efficiency.

ACE has produced positive results within the manufacturing organization. It is currently being deployed in the office environment to improve business practices at Pratt & Whitney. Four of the ACE elements have been selected for an enterprise approach to help P&W optimize its IPD process: passport, market feedback analysis, quality clinic process charts and Standard Work.[35]

There are some generally acknowledged problems with Standard Work today:[36]

Standard Work is just a list of requirements.

Some Standard Work analysis requirements are incomplete.

Content, structure and usage of Standard Work is inconsistent.

Standard Work is not part of the daily working culture.

IPT's design parts to meet the requirements in Standard Work even though it may not be complete and/or capable in all cases.

Design Reviews are a tailgate inspection that checks to see if IPT's have met the requirements listed in Standard Work.

Verification review and verification Standard Work is "after the fact"; any catches at this point delay incorporation.

[35] Jean A. Wright, "Leveraging ACE To Achieve Our Integrated Program Development Goals", Unpublished, Pratt & Whitney, July 9, 1999, 4.
[36] Ibid., 31.

As the above list illustrates, Standard Work is used in many sectors of P&W, but not all. Standard Work needs to be applied to all facets of work at P&W. Standard Work should be a continuous, current reflection of knowledge. It must be easily useable and accessible by all teams. Improvements to Standard Work should be implemented before the documentation has to used again. Both internal and external (i.e., customers and suppliers) knowledge should be incorporated into Standard Work. Everyone needs to recognize the importance of Standard Work for it to be effective.[37]

The author gathered additional comments from engineers working in the Module Centers and the Systems Engineering organizations at Pratt & Whitney. The consensus was that Standard Work is more widely used and accepted at the component level than at the system level. Perhaps this is due to the rapid organizational changes that have occurred over the past decade. Since P&W was a classic functional organization for many years, it comes as no surprise that the documentation of the core processes and components is more robust than the documentation of the Systems Engineering tasks that were formally introduced in 1997.

At the component level, Standard Work is used to plan and layout task priority in order to generate a schedule leading up to a design review. However, at the system level, it was found that Standard Work is poorly defined for analysis tasks. It does not get into the details of how the job is done to be a daily work feature. While Standard Work is formally used at component level design reviews, it suffers from incentive problems with program management at the system level. Budget, resources and/or political constraints frequently overrule system level Standard Work requirements.

[37] These challenges relative to Standard Work were obtained from the internal P&W website at http://pwww.eh.pweh.com/human_reosurces/develop/reference/ppe_ref/mainmenuandglossary/default.htm

The exact comments from individuals within the Systems Engineering organization relative to Standard Work are contained in Appendix A. These comments clearly show the absence of a Systems Engineering specific Standard Work. The causal loop diagram (negative feedback loop) in Figure 2.3a characterizes the situation today, while the diagram in Figure 2.3b (positive feedback loop) identifies the desired state that the use of the DSM can help bring about:

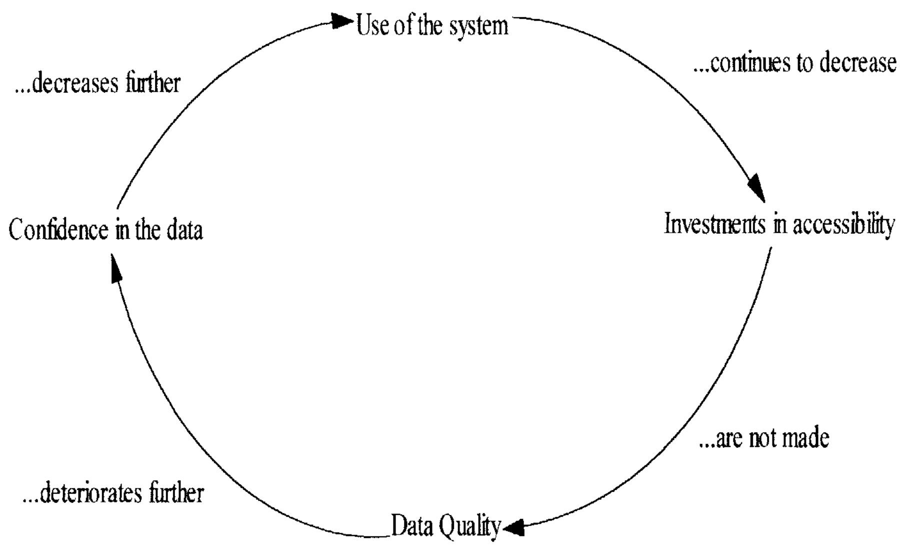

Figure 2.3a Downward spiral in an electronic knowledge base.[38]

[38] Gilbert Probst, Steffen Raub, Kai Romhardt, Managing Knowledge: Building Blocks for Success, (New York: John Wiley & Sons, LTD., 2000), 238.

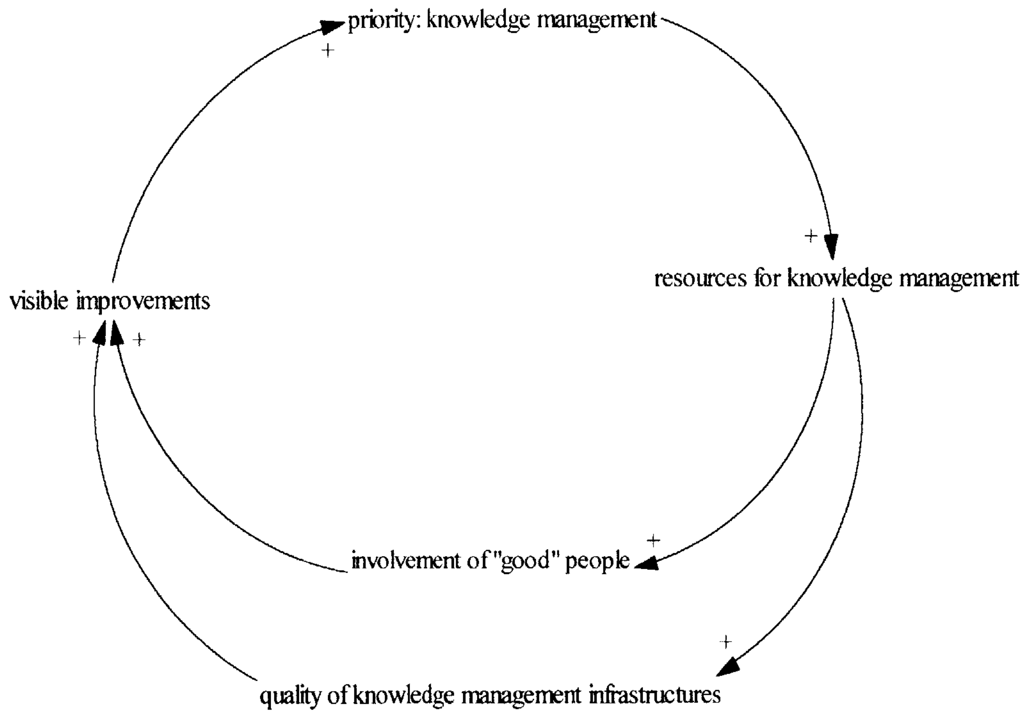

Figure 2.3b Knowledge management: "grow or go"[39]

[39] Ibid., 271.

There are currently 39 chapters to P&W's Standard Work:

1. Compression Systems, Design & Analytical
2. Turbine Component Center, Design & Analytical
3. Mechanical Components, Design & Analytical
4. Combustor, Augmentor, Nozzle, Design & Analytical
5. Control System Components, Design & Analytical
6. Externals Component Center, Design & Analytical
7. Control System Components, Design Verification
8. Mechanical Components, Design Verification
9. Externals Component Center, Design Verification
10. Nacelles, Design, Analytical, Design Verification
11. Propulsion Systems Analysis Component Center, Design & Analytical
12. Propulsion Systems Analysis Component Center, Design Verification
13. Systems Design & Component Integration, Design & Analytical
14. Systems Design & Component Integration, Design Verification
15. Compression Systems, Design Verification
16. Mechanical Components, Drafting
17. Electronic & Mechanical Systems Component Center, Drafting
18. Compression Systems, Drafting
19. Liquid Space Propulsion, Drafting
20. System Design & Component Integration, Product Definition (Drafting)
21. Combustor, Augmentor, Nozzle, Design Verification
22. Turbine Component Center, Design Verification
23. Systems Design/Advanced Engines Concepts, Design & Analytical
24. Systems Design/Advanced Engines Concepts, Design Verification
25. Turbine Component Center, Drafting
26. Project/Test Engineering
27. Liquid Space Propulsion, Combustion Chambers – Design & Analytical
28. Liquid Space Propulsion, Externals – Design & Analytical
29. Liquid Space Propulsion, Injectors – Design & Analytical
30. Liquid Space Propulsion, Mechanical Components – Design & Analytical
31. Liquid Space Propulsion, Nozzles – Design & Analytical
32. Liquid Space Propulsion, Turbopumps – Design & Analytical
33. Engineering Integrity – Design & Analytical
34. Engineering Integrity – Design Verification
35. Manufacturing Systems Engineering – CPD Launch
36. Combustor, Augmentor, Nozzle Module Center – Product Definition (Drafting)
37. Liquid Space Propulsion, Controls – Design & Analytical
38. Materials & Processes Engineering – Design & Analytical
39. Liquid Space Propulsion, Test Rigs – Design & Analytical

Chapters 19, 27-32, 37 and 39 are not applicable to this thesis as they deal with the Space Propulsion business. Of the 30 remaining chapters, only 8 address Systems Engineering in some fashion.

One initiative recently started at P&W to better link component level and system level Standard Work is Integrated Stability Standard Work (ISSW). The goal of ISSW is to develop an interdisciplinary and integrated standard work to eliminate all stability escapes in order to meet P&W's "no surge in service" committment. ISSW can be considered another chapter of Standard Work that links together the system level elements of Standard Work that address engine stability (i.e., parts of Chapters 11 and 12) to the component elements of Standard Work that address engine stability (i.e., parts of Chapters 1, 15, 18). This merging is done in the context of specifically describing the tasks to generate a stability audit, write a stability engine test plan or design/modify a schedule in the EEC software that impacts engine stability.

The detail of ISSW in describing these tasks is vastly improved relative to the content of Standard Work. However, in the review of both formats, one notable room for improvement is the need to clearly identify the customer of each process as well as the source of any required information. Similarly, an attempt should be also be made to quantify the amount of rework that could result from failure to complete the intended task.

Another improvement that ISSW has over Standard Work is that it is more closely tied to the actual product development process of P&W. Standard Work essentially only contains two references to the development process: Design & Analytical and Design Verification. The chapters of Standard Work should be closely linked to the actual development process. This process will be discussed in more detail in the next section.

Chapter 4 will attempt to show how the DSM can be used to enhance Standard Work at Pratt & Whitney.

CHAPTER 2.4 PRODUCT DEVELOPMENT PROCESS AT P&W

IPD is the standardized approach used by P&W to deploy and manage its products. It integrates all functions within the enterprise across the entire product life cycle. IPD is the primary business process that feeds off the tools provided by ACE to instill quality into day-to-day operations. In addition to defining the organizational team relationships, IPD can also be thought of as "Standard Work" for the product development process. The five major phases of IPD are:

- Planning – sets objectives, identifies priorities and provides resources.
- Definition – product and plan concepts are detailed and documented.
- Validation – assure milestones and requirements are achieved.
- Delivery – build modules and produce/ship engines.
- In Service – assure airframe and airline readiness.

The review process that assures product and program objectives are achieved is shown in Figure 2.4. The Passport reviews allow programs to be analyzed for all aspects of the venture. Product reviews occur from concept to service to assure all aspects of the product plan are achieved. Product reviews are an all-encompassing title for Part, Module and System reviews. Part reviews are held at the business center level within a Module Center. After a Part review, the issues and risks are brought up at the next Module review held at the Module Center level. Issues that cannot be resolved here are raised at the next System review. If the System review cannot resolve an issue, it is raised to senior management at the next Passport review.

This structured review process re-emphasizes the interaction that is required to optimize the design of a propulsion system. It has been criticized that this phase review process is not commonly understood and that the formats and templates are not standardized or comprehensive. Chapter 4 will attempt to show how the DSM can be used make these reviews more rigorous and help highlight potential problems earlier in the process.

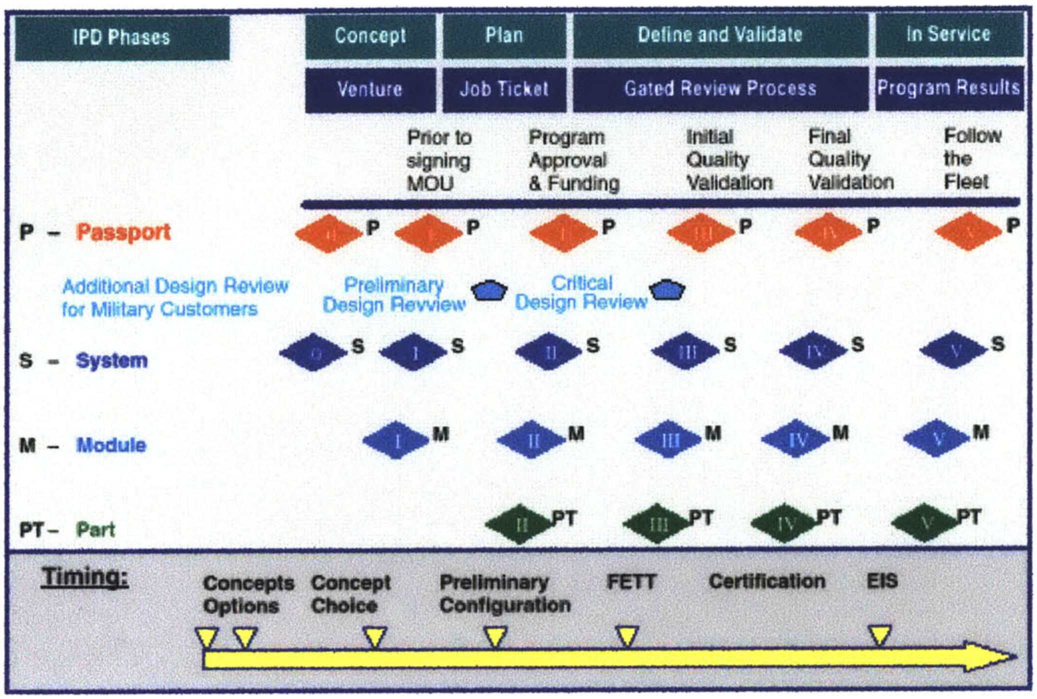

Figure 2.4 Pratt & Whitney Structured Review Process[40]

[40] Anonymous, "Operating Guidelines for Integrated Program Deployment at Pratt & Whitney", Pratt & Whitney", Unpublished, November 10, 2000.

CHAPTER 3 – RESEARCH METHODOLOGY

3.1 DESIGN STRUCTURE MATRIX (DSM)

DSM is both a systems analysis and project management tool. Donald V. Steward originally developed the Design Structure Matrix (DSM) in 1981 for the analysis of parametric descriptions of designs. DSM has also been used to analyze development projects at the task level.[41]

A Design Structure Matrix (DSM) is a compact, matrix representation of a system or project. The matrix contains a list of all constituent subsystems/activities and the corresponding information exchange and dependency patterns. That is, what information pieces (parameters) are required to start a certain activity and where does the information generated by the activity feed into (i.e. which other tasks within the matrix utilize the output information).[42]

There are four different types of data that can be represented in a DSM: components, teams, activities and parameters. A parameter based DSM is developed in this thesis. This type of modeling is used to analyze system architecture based on parameter interrelationships. A parameter DSM is constructed through explicit definition of a system's decomposed elements and their interactions. Once constructed, the parameters can be sequenced to identify couplings. An example of applying this technique to an automobile brake system design is shown in Figures 3.1a and 3.1b:

[41] Steven D. Eppinger and Karl T. Ulrich, Product Design & Development (New York: McGraw-Hill, 1995), 262.
[42] This definition can be found at http://web.mit.edu/dsm/Tutorial/DSM_reading.htm

		1	2	3	4	5	6	7	8	9	10	11	12	13
Customer Requirements	1	1												
Wheel Torque	2		2		X									
Pedal Mech Advantage	3	X		3	X	X			X		X			X
System Level Parameters	4	X			4									
Rotor Diameter	5	X	X	X	X	5		X	X		X	X		X
ABS Modular Display	6		X				6			X				
Front Lining Coef Of Fric	7			X	X	X		7	X		X			X
Piston Rear Size	8		X		X				8		X			
Caliper Compliance	9			X	X					9	X			X
Piston Front Size	10		X		X				X		10			
Rear Lining Coef Of Fric	11			X	X	X			X		X	11		X
Booster Max Stroke	12												12	X
Booster Reaction Ratio	13		X	X	X	X		X	X		X	X		13

Figure 3.1a Parameter Based DSM for Brake System (Before Sequencing)[43]

[43] Re-created from http://web.mit.edu/dsm/Tutorial/Parameter-Based.htm

After sequencing the parameters, two blocks of coupled, low level parameter determinations become apparent:

		1	4	2	10	8	3	11	7	13	5	12	9	6
Customer Requirements	1	1												
System Level Parameters	4	X	4											
Wheel Torque	2		X	2										
Piston Front Size	10		X	X	**10**	**X**								
Piston Rear Size	8		X	X	**X**	**8**								
Pedal Mech Advantage	3	X	X		X	X	**3**			**X**	**X**			
Rear Lining Coef of Fric	11		X		X	X	**X**	**11**		**X**	**X**			
Front Lining Coef of Fric	7		X		X	X	**X**		**7**	**X**	**X**			
Booster Reaction Ratio	13		X	X	X	X	**X**	**X**	**X**	**13**	**X**			
Rotor Diameter	5	X	X	X	X	X	**X**	**X**	**X**	**X**	**5**			
Booster Max Stroke	12											12	X	
Caliper Compliance	9		X		X		X			X			9	
ABS Modular Display	6												X	6

Figure 3.1b Parameter Based DSM for Brake System (After Sequencing)[44]

[44] Ibid.

The X marks indicate the existence and direction of dependency from one parameter to another. Reading across a row of one parameter identifies the parameters that the given row relies on for information. Reading down a column identifies the parameters that the given column delivers information to. Marks below the diagonal represent the forward flow of information. Marks above the diagonal reveal feedback from a downstream parameter to an upstream one.[45]

It is the intent of this thesis to show that the sequenced DSM will represent the system architecture of the engine, and therefore be used as a tool to measure P&W's knowledge management system against, as well as the product development process and technical organization.

3.2 CONSTRUCTING THE DSM

The parameter list for the system level DSM was compiled from the following sources

Design Tables

Production Acceptance Metrics

Internal Presentations

Product Reviews

Review of Previous P&W Parameter DSM[46]

Author's personal knowledge[47]

The parameters used in this DSM are the ones used primarily by the Systems Engineering organization in communicating with the rest of the organization. This is not to say that the Systems Engineering organization doesn't deal with sub-system parameters, just that the goal of

[45] http://web.mit.edu/dsm/Tutorial/DSM_reading.htm
[46] Mascoli, 94-111.

the thesis was to take a higher level view of the engine architecture. Additionally, since it is desired that the DSM be used by System Engineers in their daily work habits, it was desired to cater the parameter selection to those central to most system level discussions and correspondence.

Unlike the traditional one-on-one interview technique of constructing a DSM, a more team-based approach was undertaken to construct this DSM to assist in obtaining the desired system perspective. The team consisted of two Systems Engineers (the author, from PSA; and Douglas Hague from SD&CI) and various design experts who understood various interactions. The team assembled for at least one hour a day, 3-4 days a week beginning in early June and continuing until the end of August. At each meeting the DSM was projected from the computer onto a large screen at the front of the conference room to help facilitate discussion and keep focus on the task at hand.

The discussion that generated from these meetings proved to be a valuable learning experience. It forced consistency in the way the system was being viewed and the way interactions were being documented. The most difficult part was breaking down the mental barriers that all parameters are related to all other parameters. These discussions resulted in some initial parameters being removed from the DSM, while identifying the need to add others. The randomness of the ordering of the initial matrix is the result of this addition/deletion process. The final parameter list totaled 110 entries, up from the approximately 85 items that were included during the initial pass.

In the process of refining the parameter list it was decided that each component in the primary gaspath could be characterized by the following parameters: flow, pressure ratio,

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[47] As mentioned previously, this DSM was jointly created with Douglas Hague in support of his M.S. thesis.

efficiency and temperature profile. These parameters were also communicative to their adjacent component. It was in this manner that the indirect relationships could be decomposed to their direct links. Examples of such parameter decompositions will be discussed in detail in Chapter 4.

The final DSM (prior to any sequencing) is shown in Figure 3.2.

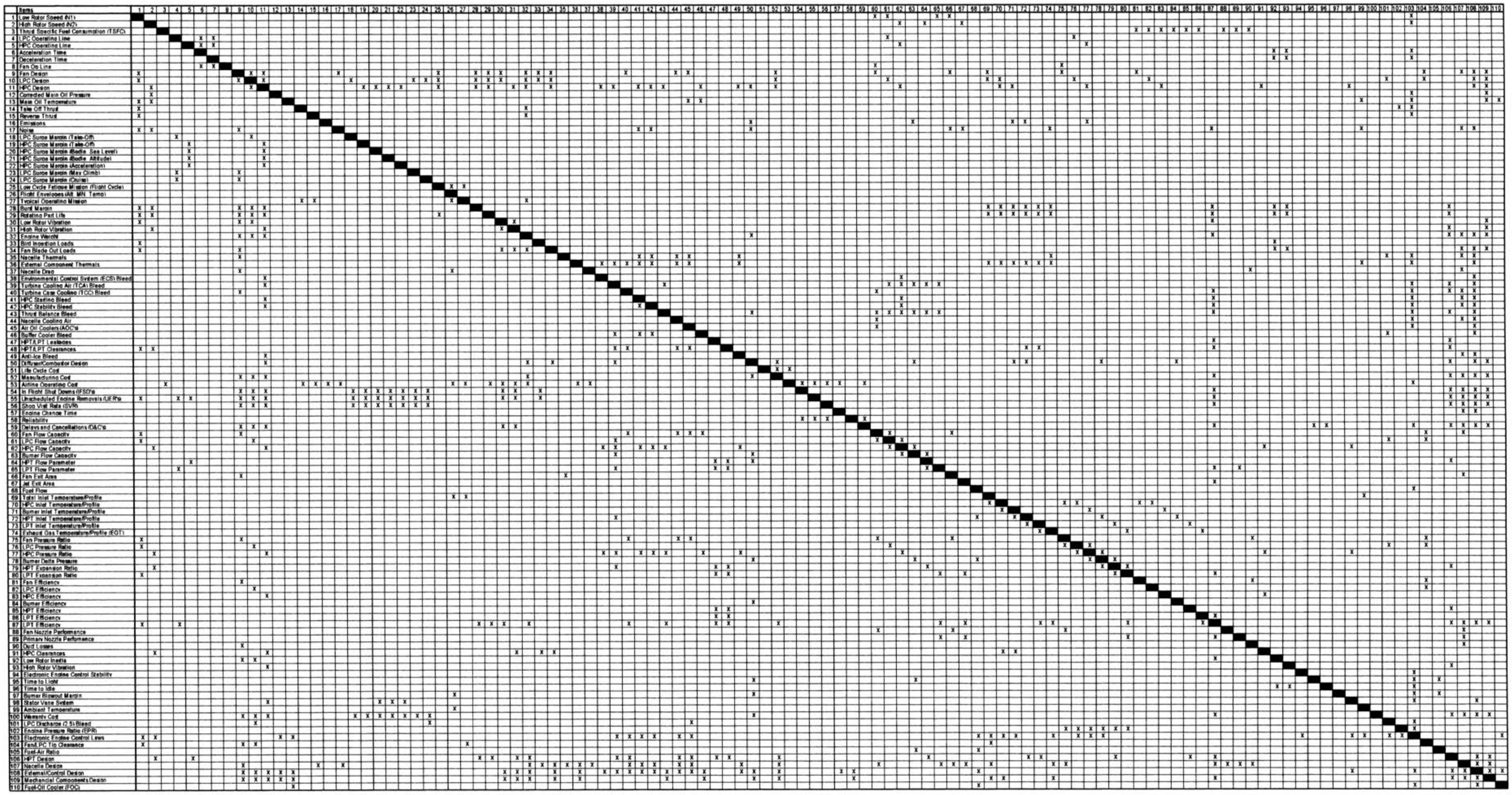

Figure 3.2 System Level Parameter DSM (Before Sequencing)

One of the other key differences between the parameter DSM created in this thesis and Gregory Mascoli's DSM is the emphasis of the matrix. The majority of the parameters used in Mascoli's DSM are descriptive of an engine in preliminary design while the parameters used in this DSM are more representative of a derivative engine design. For example, certain parameters, such as the stage count and length of the high-pressure compressor, are locked in during preliminary design and cannot be easily changed after the configuration is agreed upon. Explicit mention to these types of parameters is not contained within the DSM in Figure 3.2. Rather, all of these detailed design type parameters are grouped into one "design" parameter for each major component of the engine (fan, low-pressure compressor, high-pressure compressor, burner, high-pressure turbine, low-pressure turbine, mechanical components, externals/controls and nacelle). Additionally, the list of system level parameters in this DSM is more comprehensive due to the Systems Engineering background of the author and Douglas Hague.[48] The parameter list will be discussed in more detail in section 3.3 when the sequencing method is described.

In order to obtain confidence that the DSM in Figure 3.2 accurately represented the interactions of the jet engine, the average number of interactions per row was calculated. As observed by Daniel Whitney and his students, regardless of the type of product architecture, the average number of interactions is always 5-6 times the number of rows.[49] This statistic included matrices as small as 30 rows and as large as 1000 rows. The majority of the matrices were comprised of 40 to 110 rows and included examples from the automobile industry (throttle body, door, brakes), aircraft industry, as well as Mascoli's jet engine DSM.

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[48] The author is a member of the PSA organization while Douglas Hague is a member of the SD&CI organization.
[49] Daniel E. Whitney, Qi Dong, Jared Judson and Gregory Mascoli, "Introducing Knowledge-Based Engineering Into An Interconnected Product Development Process," (Proceedings of the 1999 ASME Design Engineering Technical Conferences, Las Vegas, September 1999), 17.

For the 110 row DSM in Figure 3.2, 814 interactions were documented, resulted in a ratio of 7.4 interactions per row. If the nine "design" parameters discussed above are excluded, the number of interactions drops to 600 resulting in ratio of 5.94 interactions per row. The good agreement with prior studies, gave re-assurance that the only the direct relationships were documented.

3.3 SEQUENCING THE DSM

Once the DSM was created, several attempts were made to sequence the DSM. The first involved using the partitioning feature of the PSM32 software tool.[50] The goal of partitioning is to re-order the matrix such that the new DSM arrangement contains less feedback marks than the original matrix. Such an arrangement will result in fewer system elements being involved in an iteration cycle thereby creating a faster development process. The matrix shown in Figure 3.2 proved to be too highly coupled for PSM32 to be able to partition without invoking the tearing feature.

Tearing is the process of choosing the set of feedback marks to remove from the matrix so that if the matrix is re-partitioned, the result will be lower triangular. The marks that are removed from the matrix are known as tears. For more on tearing, the reader is recommended to read Douglas Hague's thesis on how assumptions vary with the phase of the product development process of a jet engine.[51].

In addition to using PSM32, the reachability algorithm developed by Qi Dong was also used to attempt to partition the DSM.[52] This method attempts to find a multi-level hierarchical decomposition for the matrix. The top level in this hierarchy is composed of all elements that do

[50] Psm32: Problem Solving Matrix 3.94 – Time – © 1996-2000 Problematics/Blitzkreig Software
[51] Hague.

not require any input or are independent from all other elements in the matrix. Any two elements at the same level of the hierarchy are either not connected to each other, or are part of the same circuit at that level. For the matrix in Figure 3.2, over 100 of the parameters were part of the same circuit. This is result is consistent with the output from PSM32.

Due to the high degree of coupling, the manual clustering (re-ordering into groups of interdependent tasks) scheme used by Gregory Mascoli was adopted in favor of the above mentioned partitioning algorithms. Mascoli separated the DSM into component level parameters and system level parameters.[53] The system level parameters were isolated at the top of the matrix and the component level parameters were sequenced according to the direction of gas flow through the engine.

This scheme has been modified to include only the stakeholder requirements at the top of matrix and dropping parameters associated with the distributed architecture of the engine to the bottom of the matrix. The component level parameters remain at the center of the matrix, still sequenced according to the direction of gas flow through the engine. A diagram of this sequencing/clustering scheme is shown below in Figure 3.3. A similar pattern can also be seen in the organizational analysis performed by Craig Rowles.[54]

The power of sequencing the DSM in this fashion is that it graphically shows the distinction between local and non-local knowledge. Local knowledge is the knowledge specific to a given modular or distributed component. Non-local knowledge is the knowledge characterized by the interactions between the components (modular and distributed) and the system. These distinctions are noted on Figure 3.3. As section 2.3 demonstrated, it is the

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[52] http://web.mit.edu/dsm/Tutorial/partioning_reachability.htm
[53] Mascoli, 79.

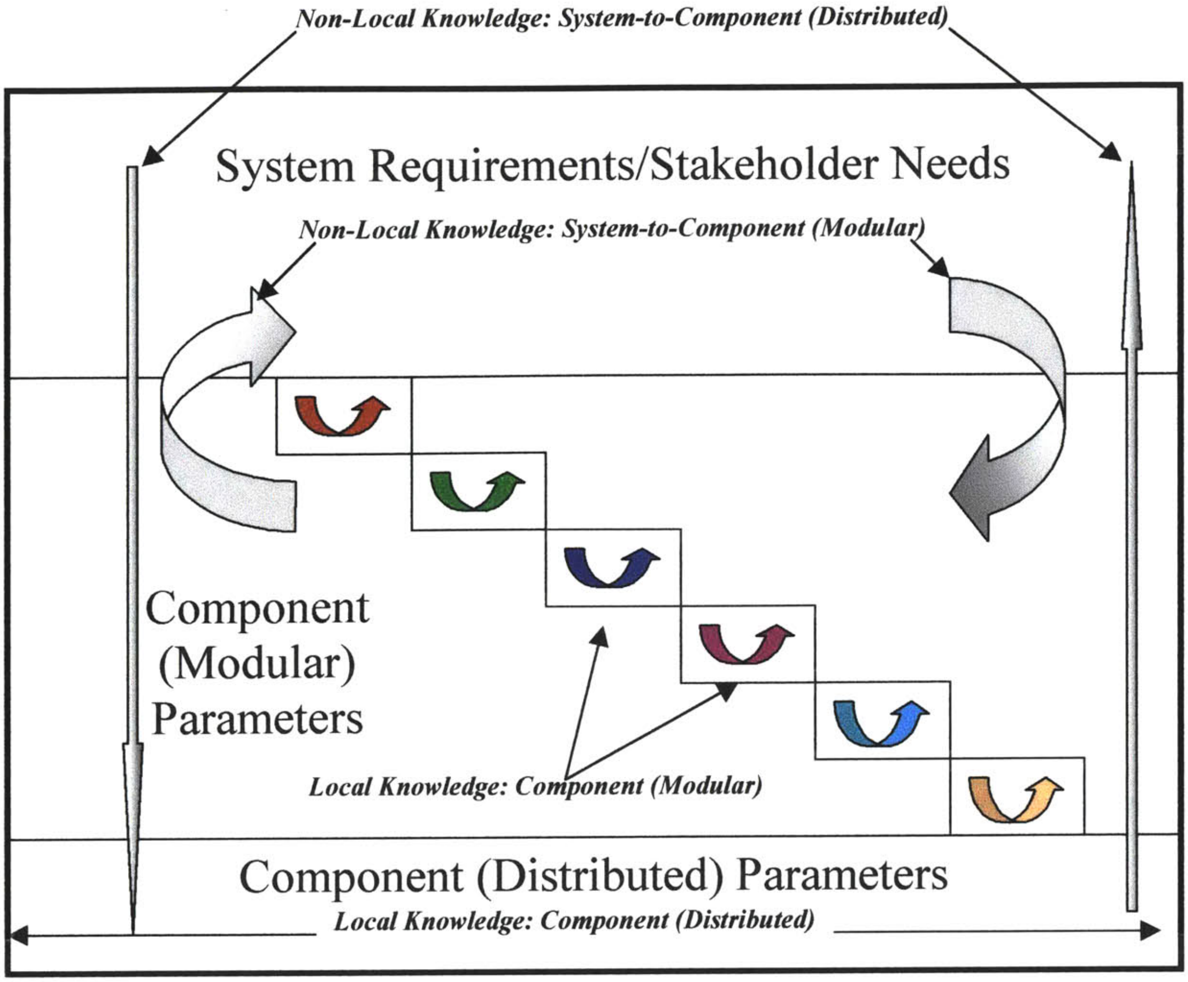

Figure 3.3 System Level Parameter DSM Sequencing Scheme & Knowledge Map

documentation of the non-local knowledge that needs improvement in P&W's knowledge management documentation.

The final sequenced DSM is shown in Figure 3.4:

[54] Rowles, 104.

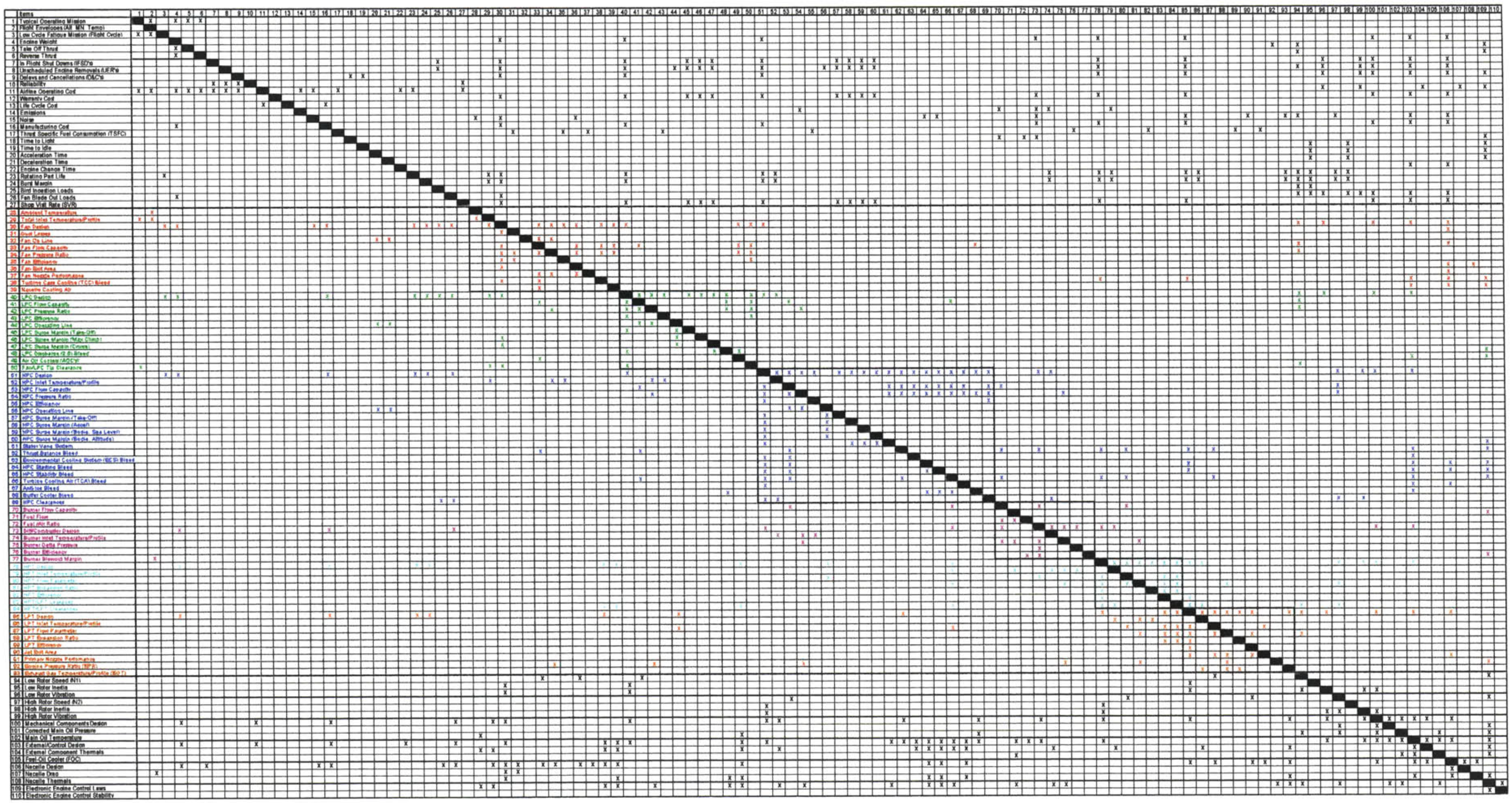

Figure 3.4 System Level Paramter DSM (After Sequencing)

The system level requirements and stakeholder needs at the top of the matrix can be divided into six categories:

Airplane Mission:	Typical Operating Mission, Flight Envelopes, Low Cycle Fatigue Mission (Flight Cycle), Engine Weight, Take-Off Thrust, Reverse Thrust
Reliability:	In-Flight Shut Downs (IFSD's), Unscheduled Engine Removals (UER's), Delays And Cancellations (D&C's)
Environment:	Emissions, Noise
Performance:	Thrust Specific Fuel Consumption (TSFC), Time to Light, Time to Idle, Acceleration Time, Deceleration Time
Design:	Engine Change Time, Rotating Part Life, Burst Margin, Bird Ingestion Loads, Fan Blade Out Loads, Shop Visit Rate (SVR)
Cost:	Manufacturing Cost, Airline Operating Cost, Warranty Cost, Life Cycle Cost

Of these six groups, only the airplane mission/integration parameters clustered nicely. The other parameters are impacted by too many other factors throughout the engine to be able to be clustered.

The modular component groupings primarily consisted of the design parameter discussed previously, as well as the parameters required to describe the flow through, pressure across, exit temperature and efficiency of each component. Pertinent sub-system parameters were added to each component as warranted by the engine design discussed in section 2.1. For example, the various air bleeds were grouped with the component that supplies the source air. The modular architecture system-level parameter groupings are as follows:

Fan: *Fan Design*
Ambient Temperature
Total Inlet Temperature/Profile
Duct Losses
Fan Operating Line
Fan Flow Capacity
Fan Pressure Ratio
Fan Efficiency
Fan Exit Area
Fan Nozzle Performance
Turbine Case Cooling (TCC) Bleed Air

	Nacelle Cooling Air
	Tip Clearance
LPC:	*Low-Pressure Compressor Design*
	Low-Pressure Compressor Flow Capacity
	Low-Pressure Compressor Pressure Ratio
	Low-Pressure Compressor Efficiency
	Low-Pressure Compressor Operating Line
	Low-Pressure Compressor Surge Margin (Take-Off)
	Low-Pressure Compressor Surge Margin (Max Climb)
	Low-Pressure Compressor Surge Margin (Cruise)
	Low-Pressure Compressor Discharge (2.5) Bleed
	Air-Oil Coolers (AOC's)
	Tip Clearances
HPC:	*High-Pressure Compressor Design*
	High-Pressure Compressor Inlet Temperature/Profile
	High-Pressure Compressor Flow Capacity
	High-Pressure Compressor Pressure Ratio
	High-Pressure Compressor Efficiency
	High-Pressure Compressor Operating Line
	High-Pressure Compressor Surge Margin (Take-Off)
	High-Pressure Compressor Surge Margin (Acceleration)
	High-Pressure Compressor Surge Margin (Bodie, Sea Level)
	High-Pressure Compressor Surge Margin (Bodie, Altitude)
	Stator Vane System
	Thrust Balance Bleed
	Environmental Control System (ECS) Bleed
	Starting Bleed
	Stability Bleed
	Turbine Cooling Air (TCA)
	Anti-Ice Bleed
	Buffer Cooler Bleed
	Tip Clearances
Burner:	*Diffuser/Burner Design*
	Burner Flow Capacity
	Fuel Flow
	Fuel-Air Ratio
	Burner Inlet Temperature/Profile
	Burner Delta Pressure
	Burner Efficiency
	Burner Blowout Margin
HPT:	*High-Pressure Turbine Design*
	High-Pressure Turbine Inlet Temperature/Profile

High-Pressure Turbine Flow Parameter
High-Pressure Turbine Expansion Ratio
High-Pressure Turbine Efficiency
Leakages
Clearances

LPT: *Low-Pressure Turbine Design*
Low-Pressure Turbine Inlet Temperature/Profile
Low-Pressure Turbine Flow Parameter
Low-Pressure Turbine Expansion Ratio
Low-Pressure Turbine Efficiency
Leakages
Clearances
Jet Exit Area
Primary Nozzle Performance
Engine Pressure Ratio (EPR)
Exhaust Gas Temperature/Profile (EGT)

For distributed component such as the rotors, only three parameters were required: speed, inertia and vibration. For the mechanical components design, oil pressure and oil temperature were added to the component grouping. For the external/control design, the thermals experienced by these components were added to the grouping. The fuel-oil cooler was also inserted into this grouping, because unlike other externals that are grouped with certain modular components, it does not use engine air or serve a primary purpose for just one of the modular components. Finally, nacelle drag and nacelle thermals were added to the nacelle design; and the EEC software is represented by the control laws and control stability parameters. The distributed architecture system-level parameter groupings are as follows:

N1: *Low Rotor Speed*
Low Rotor Inertia
Low Rotor Vibration

N2: *High Rotor Speed*
High Rotor Inertia
High Rotor Vibration

Mechanical Components: *Mechanical Components Design*
Corrected Main Oil Pressure

	Main Oil Temperature
External/Control Design:	*External/Control Design* *External Component Thermals* *Fuel-Oil Cooler (FOC)*
Nacelle:	*Nacelle Design* *Nacelle Drag* *Nacelle Thermals*
Electronic Engine Control:	*Electronic Engine Control Laws* *Electronic Engine Control Stability*

Another observation from viewing the DSM in this fashion is that it corroborates Habs Moy conclusion of the high-pressure compressor being the platform of the PW4000 family.[55] The number of interactions between the high-pressure compressor and the system requirements is larger for this component than any of the other components. Clearly, successfully developing just this one component would ensure that the majority of stakeholder needs would be satisfied.

The systems approach used in sequencing the DSM helps visualize the overall patterns more clearly. From this basis, Chapter 4 will attempt to show how the DSM can be used to prevent future escapes by adopting its use in design reviews as well as the description and incorporation of Standard Work that goes after capturing the non-local knowledge.

[55] Moy, 74.

CHAPTER 4 – RECOMMENDATIONS FROM PRATT & WHITNEY CASE STUDIES

4.1 TEST OF DSM LEGITIMACY: IDENTIFYING PAST ESCAPES

In section 3.2, preliminary confidence in the DSM was established by showing that the number of interactions was consistent with previous work. This section will build further confidence in the DSM by detailing how previous escapes are represented within the DSM, and therefore show that it is a valid model of the system level interactions of a modern, dual-spool, high bypass ratio turbofan engine.

Some escapes are simply the result of not properly assessing an impact at the right stage of the product development process. For example, one derivative design called for modifications to the burner to improve the emissions of the engine. This design change was considered a "drop-in"; i.e., that the rest of the engine would not be adversely impacted by making this change. However, the changes to the burner design resulted in changes to the pressure delta across the component. Since the high-pressure compressor exhausts into the burner, any changes to the pressure in the burner will impact the pressure ratio across the high-pressure compressor. As section 2.1 discussed, changes to the pressure ratio of a compressor result in changes to the operating line. In this instance, the resulting design change resulted in an increase to the high-pressure compressor operating line. Since a higher operating line is a threat to the stability of the high-pressure compressor, additional testing had to be performed late in the product development process to ensure that the engine still met requirements. This example can be traced through the DSM as follows, the number in parentheses following each parameter is the row/column number from Figure 3.4:

Burner delta pressure (75) ---> High-pressure compressor pressure ratio (54) ---> High-pressure compressor operating line (56)

A similar example, involving more interactions, is a case where late in the development process, it was determined that additional use of the high-pressure compressor stability bleeds would be required to correct an operability problem. However, since the change to the bleed scheduling was made so close to certification of the engine, the use of the bleed was not considered in conjunction with the following factors: operation of the aircraft's environmental control system, high ambient temperatures and deterioration. During flight testing of the engine, the combination of these factors resulted in excessive exhaust gas temperature levels. In order to correct this problem, the high-pressure compressor stability bleed logic had to be re-coded to accommodate this concern. The interactions can be mapped as follows:

High-pressure compressor stability bleed (65) ---> High-pressure compressor flow capacity (53) ---> Burner flow capacity (70) ---> Burner delta pressure (75) ---> High-pressure turbine expansion ratio (81) ---> Low-pressure turbine expansion ratio (88) ---> Exhaust gas temperature/profile (93)

Another example involving late changes to the high-pressure compressor stability bleed logic resulted in impacts to turbine durability. The new bleed schedule resulted helped the stability of the compressor by dropping the operating line. However, the reduction in exit pressure of the compressor, also reduced the source pressure of the air being used for turbine cooling. At some flight conditions, this reduction in pressure resulted in the turbine not receiving the desired cooling air. As a result, deterioration within the turbine occurred quicker than expected due to increased turbine temperatures. These interactions can be represented by the following:

High-pressure compressor stability bleed (65) ---> High-pressure compressor flow capacity (53) ---> Turbine cooling air (66) --->High pressure turbine inlet temperature/profile (79)

Another escape occurred during the initial design of the low-pressure discharge bleed (2.5 bleed) schedule, the impact of the environmental cooling system on the low-pressure compressor operating line was not properly accounted for. Had this impact been properly considered, the low rotor speed at which the 2.5 bleed is commanded open would have been increased to a higher speed. This change would have prevented some revenue service operational discrepancies. The relationships can be diagrammed as follows:

Environmental Cooling System Bleed (63) ---> High-pressure compressor flow capacity (53) ---> Low-pressure compressor flow capacity (41) ---> Low-pressure compressor operating line (44)

These previous three examples are good representatives of how past escapes at Pratt & Whitney are contained within the DSM. It is also interesting to note that relative to Figure 3.3; all of these occurrences fall into the non-local knowledge category.

Not only is the task of rewriting Standard Work to properly document all non-local interactions, beyond the scope of this thesis, but it needs to be asked is whether it is worth the investment for even a team of individuals to undertake. The number of interactions and various scenarios could result in a task that not only never be completely finished but most likely result in an unwieldy document. These two characteristics would push Standard Work more to the "downward spiral" of knowledge management discussed in Section 2.3. After commenting on an organizational observation from the matrix, the DSM will be analyzed in Section 4.3 to show how it captures these non-local interactions and can be used to prevent escapes in a variety of scenarios.

4.2 DSM INSIGHTS: ORGANIZATIONAL SUGGESTION

The first suggestion emanates from the high level of coupling of the DSM. Organizationally, this high degree of interdependence suggests the need for one chief systems engineer above today's three separate system chiefs engineer disciplines: Propulsion Systems Analysis, System Design & Component Integration and Product Development & Validation. This was recommended by Gregory Mascoli to serve the purpose of Systems Engineering being equal to the other organizational entities (i.e., Module Centers) within the company.[56] In addition to this benefit, the primary advantage of one chief engineer is that there will be one strong person in charge to make a decision regarding the intrinsic system level trades of a jet engine. This individual will also be better suited to interact with the program managers of the IPMT who are primarily driven by cost and schedule.

Additionally, most other corporations within the aerospace industry, especially airframers (i.e., Boeing or Airbus) have a chief engineer. By instituting this position at P&W, the company will better aligned organizationally with its customers. This will allow better communication to help resolve the key interface issues that always arise during integration of the aircraft and engine during development or revenue service.

The original intent of creating only a parameter DSM in this thesis was that the product architecture would be mapped to the project architecture. Since this system level parameter DSM was unable to be sequenced to represent these three separate organizational entities, it re-enforces the need for one chief systems engineer.[57]

[56] Mascoli, 87.

4.3 VALUE OF DSM: PREVENTING FUTURE ESCAPES

As alluded to at the end of section 4.1, a new type of Standard Work is required at the system level. The number of interactions and the multitude of scenarios that have to be considered by the Systems Engineering function is such that the traditional method of explicitly documenting these relationships is not the preferred method due to the scope of the task. For repetitive tasks performed at the system level, such as creating stability audits or writing a test plan, the ISSW initiative discussed in Section 2.3 is the appropriate mechanism for bringing together component specific and system-level information. It ensures consistency both across engine models and across the product development process in terms of including the right stability audit factors/methodology; and testing the appropriate conditions during operability tests. ISSW is one of the needed responses to help address the surge problem facing the company. However, Systems Engineering performs additional functions and deals with more interactions than documented in ISSW. A more holistic approach is needed to handle the problems associated with these interactions.

The DSM can help deal with the non-local interactions while simultaneously avoiding the manageability problem discussed above. It can be used as the infrastructure to capture and transfer this non-local knowledge. The primary value of the DSM is that it allows context specific views of various design issues to be taken. In addition to the examples shown previously in the validation of the matrix, more cases will be presented below to illustrate this point.

Since the DSM allows context specific views, the most beneficial use for the matrix will be in the facilitation of more rigorous design reviews. In the case of the excessive exhaust gas

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[57] During the writing of this thesis, a chief systems engineer function was created on P&W's new commercial engine, the PW6000.

temperature during hot day conditions on deteriorated engines, brought about by the use of the high-pressure compressor stability bleed, it can be seen that the right questions were not asked during incorporation of the bleed scheduling change into the electronic engine control software. This was not an isolated incident, as demonstrated in the unintended turbine cooling air reduction also brought about by a late change to the high-pressure compressor stability bleed schedule.

In order to illustrate how the DSM created in this thesis can be used to help assess all system level impacts, consider the case of a design change to the high-pressure compressor stator vane actuator that results in the actuator moving the stator vanes quicker than the original design. It is desired to be able make this design change to the actuator without requiring any other changes to the engine hardware or control software. What questions need to be asked to be able to accept/reject this design? Since the author was one of those responsible for providing concurrence on making this design change, it will be shown how the DSM could have provided much needed structure to the decision making process for this design change.

From the DSM, it can be seen that stator vane system directly impacts the following:

Stator vane system (61) ---> *High-pressure compressor design (51)*
---> *High-pressure compressor flow capacity (53)*
---> *High-pressure compressor pressure ratio (54)*
---> *External/control design (103)*
---> *Electronic Engine Control laws (109)*

Of these five items, the only two parameters that are worth exploring are the flow capacity and pressure ratio of the high-pressure compressor. The design of the high-pressure compressor is not being impacted by this particular actuator change. This parameter would be impacted if the vanes themselves were being altered. The external/control design term merely reflects the actuator re-design itself and as stated above, the intent is not to require any changes to the EEC software so the control law term does also not need to be decomposed.

The breakdown of the flow capacity and pressure ratio terms is shown below:

High-pressure compressor flow capacity (53)---> Low-pressure comp flow capacity (41)
---> High-pressure compressor design (51)
---> High-pressure comp pressure ratio (54)
---> High-pressure compressor op line (56)
---> Thrust balance bleed (62)
---> Environmental control system air (63)
---> Starting bleed air (64)
---> Stability bleed air (65)
---> Turbine cooling air (66)
---> Burner flow capacity (70)
---> High rotor speed (97)

High-pressure comp pressure ratio (54) ---> Low-pressure comp pressure ratio (42)
---> High-pressure compressor design (51)
---> High-pressure compressor op line (56)
---> Burner inlet temperature (74)
---> Burner delta pressure (75)
---> Engine pressure ratio (97)
---> Electronic Engine Control laws (109)

From the high-pressure compressor flow capacity decomposition, it can be seen that all of the bleed air systems of the compressor (thrust balance, environmental controlling system, starting bleed, stability bleed and turbine cooling) will have to be evaluated for potential transient impacts when the stator vanes are being commanded. As it turned out, the flow capacity impact on the high-pressure compressor was too small to impact these systems. The small flow capacity delta did not also prove to be an influence on the flow capacities of the adjacent components (low-pressure compressor and burner), as well as the high rotor speed. Since the position of the stator vanes only impacts the operating point on the operating line, and not the level of the operating line, the proposed change was not a threat to the stability of the high-pressure compressor. The high-pressure compressor design term was resolved in the previous paragraph so consequently, no further decomposition is required from this block.

The breakdown of the high-pressure compressor pressure ratio also reveals the high-pressure compressor design term, high-pressure compressor operating line terms and control law terms discussed previously. The other four terms only need to be assessed for transient impacts during translation of the stator vane system. Of these terms, only low-pressure compressor pressure ratio proved to be a concern. Additional modeling had to be performed to ensure that the new closure rate of the high-pressure compressor stator vanes would not be such that it would excessively back-pressure the low-pressure compressor and threaten the stability of the component.

This design change was eventually approved after resolution of the back-pressure issue concern on the low-pressure compressor. While this issue was surfaced at the right time, the identification process was not nearly as structured as the DSM decomposition detailed above. It was surfaced by the tacit knowledge of a technical expert in the Systems Engineering organization. As discussed throughout the thesis, it is the mechanism of capturing both this tacit and non-local knowledge that is lacking in existing knowledge management systems. The DSM proves to be a useful tool for performing this function.

However, the reader is cautioned that this system level DSM is based on a derivative engine design where the interactions are well known. It may not be possible to map all the interactions of a clean sheet design. However, the aircraft gas turbine engine may be the best candidate for success in using the DSM because, as mentioned in the introduction, changes to the aircraft gas turbine engine have been primarily evolutionary over the last 25 years.[58]

[58] Kerrebrock, ix.

The other advantage the DSM has in performing this knowledge transfer function is that it is easy to update (i.e., adding parameters or interactions). The previous critique of the Discipline Chief function as a supply-based approach to knowledge management would be well served by this feature of the DSM in the pursuit of instituting a demand-based system. As pointed out, the biggest obstacle with this system is that people want to get knowledge out, but nobody wants to put knowledge in.[59] The ease of updating the DSM should eliminate this as an issue. The Discipline Chiefs will still have to approve the updates to the matrix, but at least the formal task of incorporating the changes is far less cumbersome than re-writing pages of documentation.

However, in order to increase its usefulness, each interaction should be hyper-linked to a discussion of the underlying physics behind the interaction or documentation of lessons learned relative to the interaction from other engine programs. This draws upon the work of Qi Dong who used this procedure to help document her one-on-one interviews in the construction of an automobile throttle body DSM at the Ford Motor Company.[60]

One area where the DSM cannot help is that of inaccurate modeling. This may have played a role in the burner re-design example illustrated in section 4.1. The DSM currently only identifies the relationships, not the impact of the relationships. Gas turbine engine manufacturers have a tool known as Influence Coefficients (generated from an aero-thermodynamic simulation) to assist in the determining the magnitude and direction of such relationships. Influence Coefficients contain the impact (both direct and indirect) of a specified change in one parameter on all other parameters. However, these coefficients cannot be used individually to perform the

[59] Tissen, Andriessen and Deprez, 192.
[60] Qi Dong, "Representing Information Flow and Knowledge Management in Product Design Using the Design Structure Matrix," (MS Thesis, Massachusetts Institute of Technology, 1999).

decomposition performed above since the direct relationships cannot be distinguished from the others.

However, the DSM can be used in conjunction with the Influence Coefficients to help identify potential solutions to a negative impact. As an example, consider the common practice of incorporating a part from one engine to another (within the same engine family) in order to take advantage of part commonality or a beneficial feature. As much as they are advertised as "drop-ins", the parts usually have measurable impacts on other areas of the engine. For example, suppose a change is being proposed to a turbine vane in order to attain better hot-section durability. The turbine vane will impact the flow parameter of the turbine, and from the Influence Coefficients, the effect of this change can be predicted on the rest of the engine cycle. However, if one parameter is pushed over a design limit or constraint, the DSM can be used to identify what changes can be made simultaneously to offset the change. Since two changes are being analyzed, the Influence Coefficients will no longer suffice and the use of the simulation used to produce the Coefficients will be required to accurately predict the total impact.

If the high-pressure compressor operating line was the parameter pushed over the limit, the DSM could be used to identify potential changes to make to the engine. Consulting the DSM in Figure 3.4, the following parameters impact the *high-pressure compressor operating line (56)*:

Acceleration Time (20)
Deceleration Time (21)
High-Pressure Compressor Flow Capacity (53)
High-Pressure Compressor Pressure Ratio (54)

Since all of these parameters directly impact the HPC operating line, changes can be considered to these parameters to offset the increase brought about the turbine vane. As an example, if the acceleration time can be increased without jeopardizing airframer or certification thrust response requirements, then it may be possible to reduce the operating line excursion during transients to a level that would make the proposed turbine vane change acceptable. Obviously, this would be a preferred choice since it only involves changing the fuel schedule in the EEC software. These types of software changes are relatively cheaper and quicker to make than hardware changes.

This mapping of direct relationships establishes the DSM as a legitimate training device. It allows a big picture view of the engine. This can be especially useful to new engineers (or experienced engineers working on a less familiar part of the engine) to ensure that the correct questions are asked even during day-to-day activities. This can help solve problems well in advance of design reviews and make the Systems Engineering organization more process oriented. Software engineers that work on the code in the Electronic Engine Control are often looking for such tools to assist in knowing what areas to inspect when verifying that newly designed logic does not negatively impact other areas of operation of the engine. The DSM can be used to help guide these software engineers (who are not extremely familiar with how the engine functions) in this task.

Finally, the DSM proves to be a useful conduit for factoring in knowledge from suppliers and customers. The environmental control system example presented in section 4.1 is a good example. Incorporating knowledge of the aircraft (super-system) functions as early as possible during the design process will ensure that similar type integration problems are discovered prior to actual flight testing and/or revenue service.

In order to remain competitive in the "faster, better, cheaper" aerospace market, tools such as DSM will need to be adopted to ensure that escapes are caught and resolved at the right time. It is the hope of the author that the examples cited in this thesis will prove the legitimacy of the DSM in performing this function. Additional uses of DSM to achieve improved concurrent engineering are discussed in the next chapter.

CHAPTER 5 – FUTURE WORK

The vision for the DSM is that it should be the nucleus of the entire knowledge management system of Pratt & Whitney. The concept of on-line web linked DSM's that serve as directories for interaction knowledge is not new.[61] Steven Glynn and Thomas Pelland also discussed hierarchical linking of the DSM's at the IPT level.[62] However, in order to create a model that can be used throughout the Product Development Process, this idea should be extended to a higher level. The preliminary design parameter DSM created by Gregory Mascoli should be merged with the derivative engine design parameter created as part of this thesis. This would allow improved hand-off between the conceptual front-end of the process and the development stages of the process.

Regardless of the level of decomposition of the DSM, the next step of advancing the DSM's status within P&W's knowledge management system is to document the physics behind the interaction and any related lessons learned. After this information is documented, any appropriate design rules and tools should also be included. This would supplement the current initiative at P&W to link the overall aerothermodynamic simulation with the detailed module flowpath codes and give direction to how the tools should be exercised.

Such a knowledge management system would be analogous to the Integrated Multidisciplinary Design environment that corporations such as General Electric are currently striving to attain. In this environment, relevant tools/technologies and product information are integrated into a simulation environment to allow improved concurrent engineering practices.[63]

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[61] Whitney, Dong, Judson and Mascoli, 19.
[62] Glynn and Pelland, 98-106.
[63] Michael W. Bailey et al., "Integrated Multidisciplinary Design," (American Institute of Aeronautics and Astronautics, General Electric, 1999).

However the cultural issues that would be sure to surround such knowledge management systems cannot be ignored. How is a technology intensive knowledge management system integrated with the workforce? What incentive structure should be in place to ensure that motivation and creativity are not stifled as the organization becomes more process oriented? Examination of these cultural issues would make an interesting and valuable study to ensure proper attainment of the strategic benefit of such a knowledge management system.

The future form of Standard Work at the system level should resemble more of a linked, documented DSM. The flexibility and ease of update of the DSM are necessary features of any knowledge management system that is attempting to capture and manage the varied and multitude of interactions that the Systems Engineering organization deals with on a daily basis. While the current form of Standard Work at the system level is acceptable for detailed, repetitive tasks; a linked, documented and hierarchical DSM is required in today's design environment that is simultaneously striving for reduced cost, quicker cycle times and improved product performance.

GLOSSARY

2.5 Bleed	Low-Compressor Discharge Bleed
ACE	Achieving Competitive Excellence
AOC	Air-Oil Cooler
CIPT	Component Integrated Product Team
D&C	Delays and Cancellations
DSM	Design Structure Matrix
EC	Executive Council
ECS	Environmental Control System
EEC	Electronic Engine Control
EGT	Exhaust Gas Temperature
EPR	Engine Pressure Ratio
FOC	Fuel-Oil Cooler
HPC	High-Pressure Compressor
HPT	High-Pressure Turbine
IFSD	In Flight Shut Down
IPD	Integrated Program Deployment
IPMT	Integrated Program Management Team
IPT	Integrated Product Team
LPC	Low-Pressure Compressor
LPT	Low-Pressure Turbine
MIPT	Model Integrated Program Team
MIT	Massachusetts Institute of Technology

MS	Master of Science
N1	Low Rotor Speed
N2	High Rotor Speed
NAC	Nacelle Air Cooling
P&W	Pratt & Whitney
PD&V	Product Development & Validation
PSA	Propulsion Systems Analysis
PSM	Problem Solving Matrix
QFD	Quality Function Deployment
SD&CI	System Design & Component Integration
SDM	System Design & Management
SVR	Shop Visit Rate
TCA	Turbine Cooling Air
TCC	Turbine Case Cooling
TSFC	Thrust Specific Fuel Consumption
UER	Unscheduled Engine Removal

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APPENDIX A – QUESTIONNAIRE TO SYSTEMS ENGINEERING ORGANIZATION

Q. Do you use Standard Work as part of your daily work habits? If so, please indicate which sections. If not, what are the reasons why? What are the strengths and weaknesses of Standard Work?

A1. No. Standard Work is poorly defined for analysis tasks. Standard Work is a good guideline for things like setting up test programs and laying out development plans. It is poor for analysis tasks since much of what is done in operability is not cookbook or repetitive. And the things that are cookbook are generally common knowledge.
One way to improve Standard Work would be to integrate it into a more rigorous test reporting system (test results and hardware configurations reported and judged against compliance to standard work). Two other weaknesses, if we followed Standard Work to the letter test programs would become expensive and unmanageable, today's development time lines do not have enough time or assets to satisfy all elements of Standard Work. Also, Standard Work followed on a component level may not provide the best result for the system. Design compromises are often made to optimize the engine regardless of what Standard Work says.

A2. I do not use standard work as it is inconvenient and often provides only very high level guidance. Program management has no incentive to follow a recommendation just because I say Standard Work requires it. They prefer to see the data that supported the Standard Work. Generally speaking, I think I would use it more if it helped real decision making.

A3. I don't generally use Standard Work as part of my daily work habits. I find that PSA Standard Work applicable to the areas that I typically have been involved with (operability and transient test) is so general that it adds little value except to be a general checklist of issues that should be assessed. There are generally no specific procedures or guidance or detail on how anything should be done, nor any real detail on what the requirements beyond a very general sense are, just a high level list of checklist of items. Since I have experience to know what this list of items is, I have little need to refer to Standard Work very often. I also usually find that probably 60% of what I work on is some new issue/problem that has not been encountered before, and thus is not even in Standard Work. For these item I find I usually have to just figure things out on my own, as there isn't anyone else that typically knows much about them either. Since we try to continually improve and advance the technology, and new engine programs occur at very infrequent intervals, I find existing Standard Work often doesn't help with these issues. Also, even though there is Standard Work, I find it is general management practice to frequently overrule Standard Work because of budget, resources, or political constraints, regardless of what Standard Work says.

A4. Not explicitly. Standard Work does not get into the details of how the job is done enough to be a "daily" work feature. Standard Work serves more as a larger framework in which the work is done. Standard Work, in its current form and usage, is a noble idea perverted to farcical ends. Simply put, following Standard Work would produce products of excellent quality, but P&W's schedule and cost limitations will never allow Standard Work to be fulfilled 100% (and the percentage of fulfillment continues to go down as Standard Work grows and schedules and budgets get tighter). It will only improve with a major culture change regarding the development of products along the lines of the late Mr. Ito - quality should be at least as important as schedule and cost.

A5. No. Standard Work is defined to allow people who do not know how to do a task. This is not a bad thing. Standard Work documents the roles and responsibilities between organizations. Standard Work defines (clearly) work that is done with decidedly low frequency. Question is what is intent? As we grow (slowly) Standard Work I see increasing reliance on it to define tasks in the absence of local experts. Correction, work instructions are getting increased use.

Strengths

- Forces documentation of processes
- Improves ability to outsource
- Improves ability to not rely on local experts

Weakness

- Rigid requirements forces Standard Work to be too vague, resulting in decreased use of Standard Work.

Ways to improve.

- Create Standard Work/work instructions as team effort documenting outsource tasks (allows you to create instructions while getting the job done).
- Relax compliance requirements. Much Standard Work is pushed down to work instructions so enough detail can be provided to get jobs done.

A6. Systems Engineering lacks a specific Standard Work. The IPD process could be considered our Standard Work. Standard Work has the ability to strengthen the process and individuals that work within it. It can be improved by requiring that procedures be noted in analysis and recommendations and emphasizing that changes to Standard Work are allowed and encouraged when appropriate to allow innovative solutions to proceed. Standard Work is weak when it is an arbitrary obstacle (i.e., someone just wrote up the way it has always been done) that prevents progress on system level objectives.