A Systems Engineering Approach to Aero Engine Development in a Highly Distributed Engineering and Manufacturing Environment

by

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ABSTRACT

Engineering and Manufacturing firms face increasing pressure to continuously improve product development performance in terms of time to market, development cost, and customer satisfaction. The product development organization continues to evolve, first from a strictly functional focus to a product centric focus, and currently to some middle ground between the two extremes, where the strengths of the functional organization are recognized along with the merits of product focused teams. Almost simultaneously, many firms are becoming more distributed geographically and culturally, driven by internal and external influences including: efficiencies of co-location and outsourcing, business partnerships, joint ventures, and offset agreements.

As the product development organization becomes less centralized, the challenge of integrating components into the top level system becomes much more complex relative to the time when all the components were designed and built in a relatively central location. One approach to address the increasingly critical integration issues is to develop and execute a process that encourages a system level approach to product development, a process that complements the part- and assembly-level design process.

This thesis outlines the definition and implementation of a systems engineering process for jet engine development and delivery at a large aerospace company. We assess how well systems engineering manages component integration issues and determine whether it sufficiently mitigates the inherent risks associated with product development in a highly distributed engineering and manufacturing environment. The Design Structure Matrix is used to critique the tasks identified in this process as well as the plan for integrating them. We then make specific recommendations regarding: a) process enhancements; and b) roles and responsibilities of the Systems Engineering Organization to help ensure the overall success of the enterprise.

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This thesis would not exist had it not been for the support I received from Andrea Borondy-Kitts, without whose input I would not have had access to the abundant information about P&W's experiment with Systems Engineering. By allowing me to join the Systems Engineering Process Team and participate in the creation and dissemination of the Process, I was able to get a first hand view of the implementation of a major organizational and procedural change at P&W. I would also like to offer thanks to the entire Systems Engineering Process Team and numerous others who provided valuable input towards this work.

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Finishing this thesis is a somewhat bitter-sweet occasion because it marks the end of a two year journey with my SDM cohort. Thanks for the camaraderie we shared – I will especially cherish the friendships and the time spent on campus in class, in the SDM office, and at the Muddy Charles. Special thanks to Shawn Ritchie for making the final Fall memorable. Your enthusiasm and positive attitude were an inspiration, especially during those many late nights and early mornings of thesis writing.

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Chapter 1

Introduction

Engineering and Manufacturing firms face increasing pressure to continuously improve product development performance in terms of time to market, development cost, and customer satisfaction. The product development organization continues to evolve, first from a strictly functional focus to a product centric focus, and currently to some middle ground between the two extremes, where the strengths of the functional organization are recognized along with the merits of product focused teams. Almost simultaneously, many firms are becoming more distributed geographically and culturally, driven by internal and external influences including: efficiencies of co-location and outsourcing, business partnerships, joint ventures, and offset agreements.

As the product development organization becomes less centralized, the challenge of integrating components into the top level system becomes much more complex relative to the time when all the components were designed and built in a relatively central location. One approach to address the increasingly critical integration issues is to develop and execute a process that encourages a system level approach to product development, a process that complements the part- and assembly-level design process.

This thesis outlines the definition and implementation of a systems engineering process for jet engine development and delivery at Pratt & Whitney Aircraft, a division of United Technologies Corporation. We assess how well system engineering manages component integration issues and determine whether it sufficiently mitigates the inherent risks associated with product development in a highly distributed engineering and manufacturing environment. The Design Structure Matrix is used to critique the tasks identified in this process as well as the plan for integrating them. We then make specific recommendations regarding: a) process enhancements; and b) roles and responsibilities of the Systems Engineering Organization to help ensure the overall success of the enterprise

This thesis will focus on two recent changes at Pratt & Whitney Aircraft (P&W) that will enable it to move to a more geographically distributed product development process and organizational structure. The first is the establishment of Systems Engineering Groups to complement the existing design engineering organization. This organization has the responsibility of ensuring the ultimate successful integration of the system sub-components (modules). The Systems Engineering Groups are to be guided by a Systems Engineering Process; this process is a "road-map" to the system level development of an engine. System Engineering is a function that grew out of the aerospace industry of the early 1960s as a means of ensuring that large complex systems could be developed reliably without "things falling through the cracks". P&W introduced the Systems Engineering Groups in order to enhance the firm's ability to deal with integration issues that invariably arise in the development of a large complex system comprised of several smaller (but still quite large) complex sub-systems.

The second change is a move to a very highly distributed engineering/manufacturing structure called the "Module Centers". The move to Module Centers continues the evolution and improvement of the engine development process that has been underway at P&W for most of the 1990s. The currently very centralized engineering organization will soon be partitioned and distributed to several geographically dispersed factories. These factories will now have the combined responsibility for the design and manufacture of engine modules (the building blocks of an engine).

These two developments, the Systems Engineering Groups and the move to Module Centers, are inextricably linked because the success of the latter is very much dependent upon the ability of the former to fulfill systems integration and boundary management roles in the distributed organization.

Before the Module Center concept, the entire design engineering organization was co-located, with engineers working on a particular engine model together on the same floor of a single engineering building. There was formal, structured systems integration work in progress with formal mechanisms in place to support it, as well as a lot of informal, unstructured systems integration work with informal support mechanisms. While systems integration was relatively strong in this organizational structure, the integration of design engineering and manufacturing was weak. Manufacture of the engine hardware was conducted at "Product Centers", where all the other activities directly related to the manufacturing process resided (e.g. manufacturing process development, tool design, and quality). With the move to Module Centers, P&W may have figured out how to strengthen engineering/manufacturing integration, possibly even being able to eliminate the labels of "engineering" and "manufacturing". In the Module Center, the focus of the entire team is on the design and production of the *module*, while meeting performance, cost, weight, delivery, quality, and customer satisfaction goals. But what about the engine *system*?

For all the promise that the Module Center concept holds, P&W must recognize that a trade has been made. Engineering/Manufacturing integration will be achieved to a high degree in the Module Center, but possibly at a cost of system integration capability. The key to the success of the new structure is to ensure the primacy of the system. P&W management has recognized that there is a risk that system integration has been traded for engineering/manufacturing integration. By the creation of the systems engineering function and the systems engineering process, they have figured out that these do not have to be mutually exclusive. The premise is the following: by doing systems engineering properly, P&W can have the benefits of both structures: engineering/manufacturing integration via co-location of the roles in the module center, and systems integration through the efforts of the Systems Engineers across the various module centers.

1.1 The Gas Turbine Aero Engine

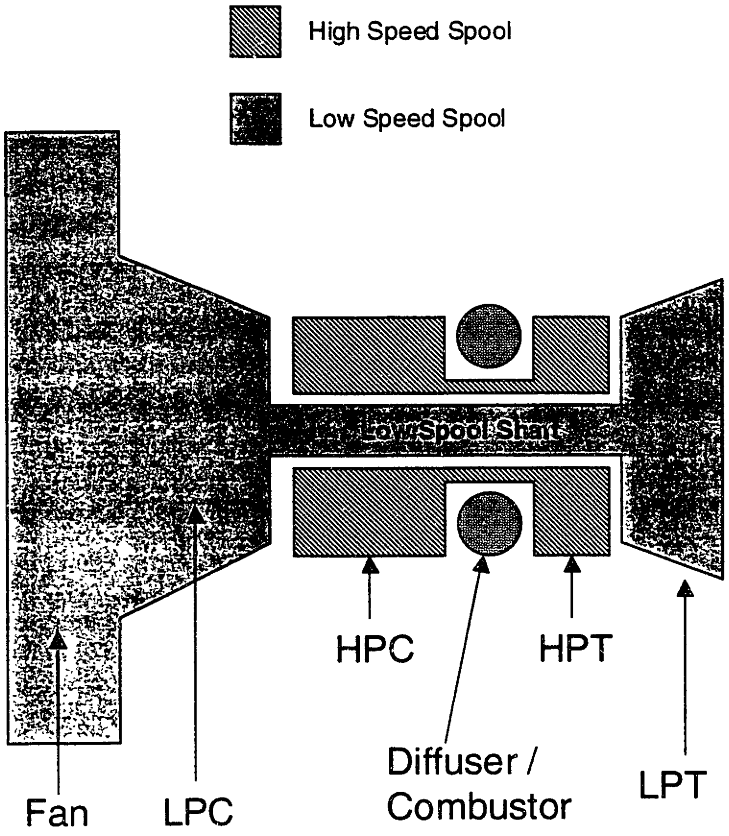

Figure 1-1
Gas Turbine Engine Cross Section

It is appropriate at this juncture to provide the reader with a bit of insight into the operation of the gas turbine aero engine; a more detailed discussion follows in Chapter 4. Figure 1-1 shows a simplified cross sectional view of a modern two-spool high by-pass turbofan engine used by most commercial airliners today. The engine components perform three primary functions that enable to engine system to provide propulsive thrust to the aircraft: 1) compression of a gas (air); 2) combustion of the compressed gas: 3) exhaust of the combusted gas.

Compression of the gas is accomplished by the Compression Systems Module. This module is comprised of the following components:

- **Fan**: provides for initial intake of air, 15% of which feeds the combustion process, 85% of which by-passes the engine core and provides greater than 90% of the overall engine thrust;

- **Low Pressure Compressor**: first component in the engine core, decelerates gas flow and raises gas pressure;
- **High Pressure Compressor**: second component in the engine core, further decelerates and compresses the gas.

When the compressed gas leaves the High Pressure Compressor, it has reached its highest pressure in the engine and enters the Diffuser/Combustor Module where the gas is mixed with fuel and then burned in the Combustor.

The final step in the process is the Exhaust of the combusted compressed gas/fuel mixture through the Turbine Systems Module, consisting of the High Pressure Turbine (HPT) and Low Pressure Turbine (LPT). As the combusted gas flow exits the Combustor, it first passes through the High Pressure Turbine. The High Pressure Compressor and High Pressure Turbine are mechanically coupled through a shaft between the two components, and the HPT extracts enough energy from the flow exiting the Combustor to drive the HPC. The flow then passes through the Low Pressure Turbine and then exits the engine. The Fan, Low Pressure Compressor and Low Pressure Turbine are mechanically coupled through the Low Speed Spool Shaft that runs axially much of the length of the engine. The Low Pressure Turbine extracts enough energy from the exhaust flow to drive the Fan and LPC at the front of the engine.

1.2 Phases of the Engine Development Process

In the commercial aero-engine business the engine development process starts with a set of requirements from an airline customer and/or the airframer (Boeing or Airbus). These propulsion system requirements are very high level in nature, and typically address in very simple terms such things as the proposed market and potential competition, number or seats and the range of the proposed airframe application, target operating costs (e.g. dollars per available seat mile), purchase price, noise requirements (which strongly impact access to certain lucrative routes), weight, and Airline Direct Operating Cost. Later, during the Conceptual Design phase, decisions about Thrust, By-Pass Ratio, Overall Pressure Ratio, fuel burn requirements, and other high-level parameter decisions are being made based on these high-level system requirements.

This information becomes available to P&W during what may be referred to as the "Input Phase" of the product development process. Marketing and Sales and Advanced Engine Programs personnel are heavily involved, as well as the P&W Executive Committee, the group that decides whether to move on the next phase, Conceptual Design, based on the economics of the proposed propulsion system (e.g., market potential, expected development costs). When the Executive Committee determine that the program is worth pursuing, the Conceptual Design Phase is where Advanced Engine Programs creates and evaluates various engine concepts that can meet the overall system requirements. It is during this stage that such system level target parameters start to be initially defined. These system level parameters might include system weight, thrust, and fuel burn. From a number of feasible concepts, the one with the greatest potential for success is down-selected and enters into the Preliminary Design, still with the Advanced Engine Programs Group, but now with additional help from the mainstream (i.e. not Advanced Programs) engine program personnel who assist with providing historical data, running more complex analyses, etc. It is during the Preliminary Design phase that engine architecture becomes very firm and enough target parameters are defined to allow Detailed Design of the engine components. As the development process moves into Detailed Design, the engine program is considered officially 'Launched" with full engineering design and development assigned for the work on each component. Detailed Design moves on into a Validation & Verification Phase where the engine is put through various performance, operability, endurance, and verification testing to uncover and correct any design errors and to fulfill the comprehensive requirements of the regulatory agencies that oversee the operation of these engines and aircraft (Federal Aviation Administration in the United States, Joint Aviation Administration in Europe). Once the engine has completed ground test and flight test successfully it can begin its production run during the Production and Field Service Phase of the life cycle. Modern aero engines remain in production for many years. The JT8D that was developed in the 1960s is still in production at P&W.

Target values for the parameters analyzed in this thesis are set by engineers in the Advanced Engine Programs group prior to the Detailed Design phase of an engine program. Some of these parameters are less firm than others, and will certainly change during the downstream phases of the engine design and development process. In fact, these parameters continuously come into play as the Program moves through Detailed Design, into Validation and Test, and very importantly, when the engine system is out in the field (e.g., response to field issues). It is our opinion that the parameters captured in the analysis are important to the System Engineer even if he/she was not involved in the initial design of the engine.

The role of the Systems Engineers is to ensure that component integration is flawless by quickly and decisively addressing system level issues. It is commonly accepted that the operation of the gas turbine engine is a function of how well the components work together. We shall demonstrate this coupling between components in the later chapters. Inter-component design issues result from this coupling. In many instances these issues can be resolved among the immediate stakeholders, for example, members of the component teams. But in other instances, the solution may be very complex and not completely obvious to all the stakeholders. In such instances the Systems Engineers are called on to make the technical decision that optimizes the system rather than the component design. This "boundary management" role becomes increasingly important when the component teams are geographically distributed at Module Centers, because inter-team communications are significantly reduced when teams are distant from one another.

1.3 Goals of this Thesis

This thesis will attempt to address some of the important issues that will arise as the Systems Engineers address their roles as the "glue" that holds the new distributed engineering/manufacturing organizational structure together. By analyzing the parameter interactions and information flows that exist in the development of the individual engine components, we will attempt to identify some of the interface issues that the Systems Engineers must address as they attempt to integrate components designed and manufactured by geographically dispersed development teams. In addition, by understanding the inter-component interactions and the impact system level parameters have on the various components (and vice versa) we expect to derive some understanding of how the Systems Engineers must function strategically and tactically to manage the system level issues. We intend to show that while the Systems Engineering Groups and the Process are fairly well defined there are significant areas for improvement related to the Module Center structure and the product development challenges that geographic distribution of the component teams introduces.

The remainder of this thesis is organized as follows. Chapter Two will review the evolution of the product development organization at P&W over the past 8-10 years. Chapter Three will provide a summary of various tools available to system designers for mapping the product development process. Several tools will be considered, with the Design Structure Matrix (DSM) chosen for further use in this thesis for evaluation of various system design processes. Chapter Three presents a brief introduction to the Design Structure Matrix, its origins in the systems engineering literature, expansion of its application through the work of several researchers at MIT, and an explanation of its construction and interpretation.

Chapter Four will provide background on the aero-engine System Design process, with a discussion of the decisions and parameters that drive the overall system level design. The Design Structure Matrix is used to identify blocks of inter-related design parameters and provides insight into the level of interaction between. We examine the question of whether the component teams must be co-located, distributed, or a combination the two, depending on the phase of the program. We determine that co-location is necessary during the Conceptual and Preliminary Design phases, but that distributed component design can occur in later phases, once a comprehensive set of system and component requirements has been defined, and some mechanism for communicating changes to these requirements is in place. Finally, the DSM is partitioned into regions that define the domain of the Systems Engineers, the component teams, and both in conjunction, thus helping to better define the overall Systems Engineering Process.

Chapter Five reviews the implications of an organizational change at P&W, namely the implementation of the Systems Engineering Groups to complement the existing design engineering organization at P&W. We review the definition of Systems Engineering at P&W, the roles and responsibilities of the Systems Engineers, and review the Systems Engineering Process that is envisioned to be used as a road map to guide the Systems Engineers in their new roles. Chapter Six attempts to link the activities in the Systems Engineering Process to the actual design parameters and decisions about those parameters that are outlined in the DSM in Chapter 4.

Chapter Seven summarizes the findings revealed by the DSM analyses and makes recommendations regarding the roles and responsibilities of the Systems Engineers that are suggested by the information and task dependencies uncovered in the preceding analyses. We also suggest future work that could be undertaken to further streamline the development process, reducing the overall cost and time required for aero engine development.

Chapter 2

Industry Context - Pratt & Whitney Aircraft

2.1 Background

Pratt & Whitney Aircraft (P&W) is a division of United Technologies Corporation (UTC), based in East Hartford Connecticut. P&W has a 4500 person engineering department, with engineering operations in East Hartford primarily for commercial aero engines, and in West Palm Beach Florida for military and space applications. P&W also maintains five manufacturing centers: 1) Middletown, CT; 2) East Hartford. CT; 3) North Haven, CT; 4) North Berwick, ME; and 5) Columbus, GA., and a globally distributed supplier base.

Domestic and international customers of P&W are comprised of major airframers (e.g. Boeing and Airbus) and global airlines. The challenges P&W faces today are similar to those faced by other high technology manufacturing firms: quicker delivery of innovative products to the market that deliver greater value to the customer than past products. The future viability of P&W is dependent upon the firm's ability to provide the most dependable and highest value propulsion systems to its customers. Among other goals, P&W is committed to a continuous reduction of time between customer order and product delivery; the highest product reliability in the industry regardless of measurement metric; and innovative customer and fleet service products. Achievement of these goals requires significant changes in P&W's manufacturing and technical (engineering) organizations.

Tables 2-1 and 2-2 summarize the major product offerings P&W has made to the commercial and military markets over the last three decades. P&W continuously strives to provide its customers with propulsion systems covering the entire thrust range required by the contemporary production airframes, matching airframe and mission requirements.

Table 2-1: Pratt & Whitney Commercial Engines Product Line

Engine Model	**Type**	**Thrust Range (Pounds @ Take Off)**	**Aircraft Powered**
JT3D (out of production)	Turbo-Jet	17000-19000	B707, B707-200, B720, VC-137C, DC-8
JT8D-1 through -17 (out of production)	Turbo-Jet	14000-17400	B727, B737, DC-9, Caravelle 10B and 12, T-43A, C-9A, VC-9C, Mercure
JT9D (out of production)	Turbo-Fan	48000-54750	B747, B767, A300-600, A310, DC-10
JT8D-200	Turbo-Jet	18500-21700	MD81, MD82, MD83, MD87, MD88, Super27
V2500 (International Aero Engines)	Turbo Fan	25000-33000	A319, A320, A321, MD90
PW2000	Turbo Fan	37000-43000	B757, IL-96, C17
PW4000-94" Fan	Turbo Fan	52000-62000	A300, A310, B767, B747, MD-11
PW4000-100" Fan	Turbo Fan	64000-68000	A330
PW4000-112" Fan	Turbo Fan	74000-98000	B777

Table2-2: P&W Military Jet Engine Experience

Engine Model	**Type**	**Aircraft Powered**
J42	Turbo Jet	F9F-2
J48	Turbo Jet	F9F-5, F94C,F9F-6, F9F-8
T34	Turbo Jet	C133, C-97J, C121F
J52	Turbo Jet	AGM-28B, A-4, TA-4, A-6, EA-6B
J57	Turbo Jet	F-100, F-101, F-102, A-3D, F-8, B-52, KC-135, U2, SM-62, F4D, F5D, C-135
J58	Turbo Jet	SR-71, YF-12A
J60	Turbo Jet	C-140, T-39A, T-2B
J75	Turbo Jet	F-105, F-106, TR-1, F-107A
TF30	Turbo Jet	A-7, F-111, F-14A, EF-111, FB-111
TF33	Turbo Jet	C-135B, C-141A, B-52H, E-3A, EC-135, RB-57F, VC-137, E-8
F100	Turbo Jet	F-15A/B, F-16A/B, F15C/D, F16C/D, F-15E, LAVI
F404	Turbo Jet	F-18
F119	Turbo Jet	F-22, JSF

2.2 Evolution of Product Development Organization/Process at P&W

The Aero-engine business is similar to the American automotive industry in many ways with respect to the market forces driving internal change in the area of product development. Both industries face pressures to lower costs, improve quality, reliability, and performance of their respective products. The commercial aerospace industry is strongly driven by international macro-economic forces. In good times, airline customers will be placing orders with airframers, which in turn translate into orders for the aero-engine manufacturers. Airplanes take a long time to build; and the order fulfillment time (the time between order and delivery of an airplane) can be as long as 4 to 6 years. In the intervening time period, the fortunes of the airline may take a turn downward, possibly due to a recessionary period hitting the home country or region in which the airline operates. In response the airline cancels or delays orders for aircraft, which again eventually impact the aero-engine manufacturer.

This cycle has been repeated (and documented) many times in aviation history. The airlines place aircraft orders when they have cash and are strong, only to have to cancel or postpone orders when the delivery dates approach. This cycle is costly (and therefore very disconcerting) for the firms that try to remain profitable in the aerospace industry. In response to this problem, the airframers have become very interested in reducing the time it takes to develop and build a new airplane. This reduced product development cycle time at the airframer has put equal pressure on the engine manufacturers and other suppliers to the airframers to reduce their cycle times.

2.3 Evolution of the Product Development Organization at P&W[1]

P&W's product development organization and process has been in a state of intense evolution over the past eight years in an effort to meet the market demand of reduced development cycle times and costs. The following section walks the reader through these significant organizational changes, which have occurred approximately every two years since 1990.

2.3.1 The Functional Organization (Pre-1990)

Through 1990, the design engineering organization was functionally oriented. Within functional groups, an engineer might specialize in design of a particular type of hardware (e.g. turbine blades or compressor cases) or a specific type of analysis (e.g. aerodynamics, structural dynamics). Engineers were hired into functional groups and tended to spend their entire careers developing their skills in the particular area and progressing through the ranks of the group hierarchy. Each functional group had its own management hierarchy and culture, and movement from one functional area to another was not all that common. People had extremely strong allegiance to the home organization and took great pride in their work, as is common in a functional organization. In some ways these ties were legitimate, considering the many years in a function required to develop sufficient background to be considered an expert (having participated on several designs, covered test and develop. certification programs, dealt with production and field problems, etc). In addition, having a key job requirement to "develop state-of-the-art techniques and analyses" helped promote a feeling that one's work was expected to be superior to all other's in the field. Figure 2-1 shows a view of the 1990 Functional Organization within design engineering.

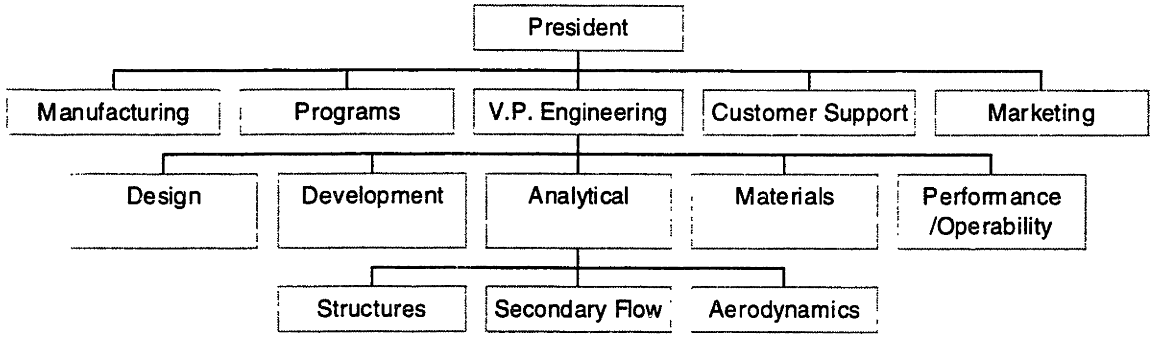

Figure 2-1
Pre-1990 Functional Organization

The benefits of this functional organization structure were:

- Technical excellence in each function;
- Employee feeling of identity derived from belonging to the functional group;
- Explicit career path within the functional organization;
- Employees understand expectations;
- Management has flexibility to move resources among the engine programs as needed.

But these benefits were outweighed by some of the difficulties caused by the functional focus:

- Functional chimneys that slow progress and make it difficult to manage the product development process;
- Too many hand-offs and loss of control points in the process making the design and development process inefficient;
- Engineers are functionally oriented not product oriented which leads to doing the things that advance the state of the art of the function, with product improvements secondary.

In this organization, the focus of the design engineering community was on functional disciplines (e.g. aerodynamics, structures). There was centralization of the functional groups, for example, all aerodynamicists seated together. Each functional group was partitioned into engineers covering all the various engine programs; therefore we would consider the Program structure distributed. From a manufacturing perspective, there was little design engineering/manufacturing integration.

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[1] Much of the discussion in this and the following sections on the evolution of the product development organization is derived from a presentation given by Paul Greenberg at USC in November 1997.

2.3.2 IPD – Component Integrated Product Teams (1991-1993)

In 1991 Integrated Product Development came to P&W and design engineering was reorganized from the functional groups to an engine component focused organization. Component Integrated Product Teams (CIPT) were created, comprised of several Integrated Product Teams (IPTs)[2]. The CIPTs are staffed with individuals from all the functional groups. All the key players are present from the inception of a program to develop the new product. Customer Support and Manufacturing Operations representation have been included to help identify and avoid potential manufacturing or service related problems early in the development process. In some instances there has even been supplier representation on the CIPT.

Each engine program has the following CIPTs that are responsible for production cost, reliability, maintenance cost, performance and operability, weight, noise, emissions, schedule, design life, and verification associated with its component. More specifically, some of the major hardware responsibilities of the CIPTs are as follows:

- <u>Fan CIPT</u>: Fan Blades, Fan Hub, Containment System, Fan Exit Guide Vanes, all associated by-pass flow ducting, etc.
- <u>Low Pressure Compressor CIPT</u>: LPC airfoils, disks, cases (including intermediate case), bleed systems.
- <u>High Pressure Compressor CIPT</u>: HPC airfoils, disks, variable geometry vane system, bleeds, cases.
- <u>Diffuser/Combustor CIPT</u>: Diffuser Case, Combustor structure, Fuel Nozzles.
- <u>High Pressure Turbine CIPT</u>: HPT Airfoils, disks, cases.
- <u>Low Pressure Turbine CIPT</u>: LPT Airfoils, disks, cases, low spool shaft.
- <u>Externals and Controls CIPT</u>: External plumbing (fuel, hydraulic systems), engine control system (hardware and software).
- <u>Mechanical Components and Systems CIPT</u>: Rotor support systems, bearings, seals.

The shift to the CIPT organization was difficult for many in engineering. The functional groups were easy to understand and made sense to almost everyone. There was a feeling that while the new organization may have its strong points, the disintegration of a system that had worked in the past was bad, and the negative attributes outweighed the benefits of cross functional teams, co-location of discipline by program, etc.

In this organization, the focus of the design engineering community is shifted from parts (e.g. blades, cases) to complete components (e.g., compressors, turbines). There is centralization of the component groups with the CIPTs and also of the engine programs, as all engineers involved with a particular program are co-located in the engineering building in East Hartford (the functional groups are now distributed). From a manufacturing perspective, there was little design engineering/manufacturing integration.

2.3.3 Component Centers and Product Center Engineering

This section describes the move to the Component Center and Product Center Engineering structure in 1993 which is the predecessor of the Module Center structure that will be put in place starting in 1999. The Component Center/Product Center structure ushered in the concept of a distributed engineering organization at P&W.

2.3.3.1 Component Centers (1993-present)

Component Centers were formed in 1993 as cross-functional teams with engineering, manufacturing and customer support representation. The Component Center Directors report to the V.P. of Engineering. Each Component Center has its own set of CIPTs associated with the Component Center hardware and each Engine Program. Although reporting is through Engineering, day-to-day program direction is though the Integrated Program Management Team whose leadership reports through the V.P. of Engine Programs. A brief review of each of the Component Centers is provided below.

Compression Systems Component Center (CSCC)

The Compression Systems Component Center is responsible for all aspects of the design, development, and post certification activities for all Fans, Low Pressure Compressors, and High Pressure Compressors for each engine program.

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[2] Note that with all of the organizational changes that have taken place from 1991 through 1998, the CIPT

Turbine Systems Component Center (TSCC)

The Turbine Systems Component Center is responsible for all aspects of the design, development, and post certification activities for all High Pressure Turbines and Low Pressure Turbines for each engine program.

Electrical & Mechanical Systems Component System (EMCC)

The Electrical & Mechanical Systems Component Center is responsible for all aspects of the design, development, and post certification activities for all Electrical and Mechanical Systems including Fuel Controls, Engine Controls, External plumbing, Bearings, Seals, etc.

Combustors/Augmentors/Nozzles Component Center (CANCC)

The Combustors/Augmentors/Nozzles Component Center is responsible for all aspects of the design, development, and post certification activities for all Diffusers, Combustors, Fuel Nozzles, (and augmentors-after burners and variable geometry nozzles found on military aircraft engines.

One of the by-products of the creation of the CIPTs and the co-location of Engine Programs was enhanced systems integration capability. In this structure, all the engineers working the design of an engine were seated on a single floor in a centralized engineering building in East Hartford Connecticut.[3] This close proximity has facilitated communications between CIPTs through both formal and informal mechanisms. The formal mechanisms include CIPT and IPT meeting in which members from outside the CIPT or IPT can easily be invited to participate, even at short notice. Informal mechanisms might include impromptu discussions amongst team members over coffee or lunch.

The Program Management structure is shown in Figure 2-2. There is a split between the technical organization and the program management roles. All funding flows through the Program office to the IPMT, The Integrated Program Management Team, responsible to the VP of Engine Programs for all of the business management aspect of running the engine program. As is shown in Figure 2-2, the technical skills are provided by the CIPTs to the IPMT. The IPMT has the authority to charter the CIPTs, determine task assignments, etc.

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structure has survived in the form described here.

[3] Recall that we are focusing on the commercial engine development in this thesis.

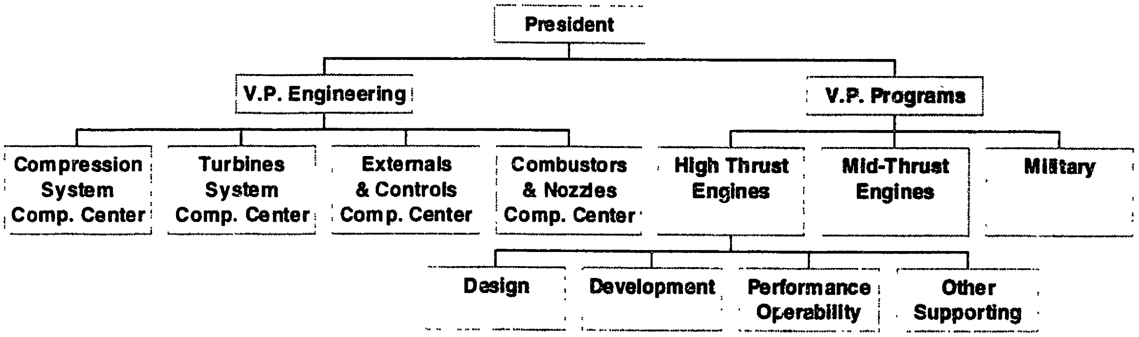

Figure 2-2
Component Center Reporting Structure.
Technical Organization Separate from the Program Management Organization

The benefits of this structure were that the efficiency of cross-functional teams was leveraged because all the right people for the design of a specific component resided within the Component Center and were readily available. Also, within the Component Center, engineers were focused on a specific engine program. On the downside, there was now a split between technical (engineering) management and the program management. What is right for a specific program may not be what's right for the Component Center (resource allocation in terms of manpower and budget for example, or cost reduction versus new product development needs). There were also serious concerns about the creation of new functional chimneys within each Component Center, defeating the purpose of Integrated Product Development. Simultaneously there was the fear that there would be a net loss in discipline capability (e.g., structures, aerodynamics) over time.

In this organization, the focus of the design engineering community shifted squarely to components (e.g. High Pressure Compressors, Low Pressure Turbines). There was centralization of the component groups with the CIPTs and also of the engine programs, as all engineers involved with a particular program were still co-located in the engineering building in East Hartford. From a manufacturing perspective, there was still little in the way of design engineering/manufacturing integration.

2.3.3.2 Product Centers and Product Center Engineering (1995)

While Design Engineering had organized around the Components, Manufacturing Operations changed its focus to part families during the same timeframe in the early 1990s. In the

Manufacturing Organizational structure, the Product Centers were organized around the types of parts they make, were defined as follows:

1) Stators Product Center, North Berwick, ME
2) Cases & Combustors Product Center, Middletown, CT
3) Rotors & Shafts Product Center, Middletown, CT
4) Externals and Nacelles Product Center, Middletown, CT
5) Turbine Airfoils Product Center, North Haven, CT
6) General Machining Product Center, E. Hartford, CT
7) Composites Product Center, Rocky Hill, CT
8) Compressor Airfoils Product Center, Middletown/Georgia
9) Worldwide Procurement: Suppliers

Table 2-3 summarizes the distribution of engine hardware sources across the Product Center structure.

Table 2-3
Distribution of Engine Hardware at Product Centers

	Fan	LPC	HPC	Diff/ Comb	HPT	LPT	Externals
Stators, N. Berwick,		X	X		X	X	
Cases & Combustors, Middletown, CT	X	X	X	X	X	X	X
Rotors & Shafts, Middletown, CT	X	X	X		X	X	
Externals & Nacelles, Middletown, CT	X	X	X	X	X	X	X
Turbine Airfoils, N. Haven, CT					X	X	
General Machining, E. Hartford, CT	X	X	X	X	X	X	X
Composites, Rocky Hill, CT	X	X					X
Compressor Airfoils, Middletown & GA	X	X	X				
Worldwide Procurement	X	X	X	X	X	X	X

This Manufacturing organizational structure was put in place to take advantage of the similarities in processing and skills, both in engineering and on the shop floor, among parts belonging to the same parts families. Characteristics of a Product Center:

- Parts family focus (rotors, cases, blades)
- Personnel includes Manufacturing Engineers, Tooling, Quality, Production (hourly associates, cell leaders, etc)
- No design responsibility except to participate on IPTs which were not stationed at the manufacturing site, rather in East Hartford.

January 1995 Product Center Engineering was established and Design Engineers were co-located at the manufacturing sites. Recognition that 80% of the cost of the product is committed during the Preliminary and Detailed design phases led to the need to have Product Center Engineers represented at the Manufacturing sites, in addition to manufacturing representation on the IPTs. The goal was to provide closer ties between design engineering and manufacturing, but in turn created a shortage of manpower to staff the CIPTS and IPTs, and there was a shortage of engineers in manufacturing.

The move to Product Centers and in particular Product Center Engineering with personnel supplied by the CIPTs started a process of integrating the design engineering and manufacturing communities.

2.3.4 Systems Engineering Groups (1997)

The Systems Engineering Groups were introduced at P&W in the Spring of 1997. They were created to augment the Component Center structure that had been in place since around 1993. P&W management had assessed the performance of the Component Centers and determined that with a focus on component development, overall system integration issues were not getting the attention they deserved during the development process. The Systems Engineering Groups were introduced to address the integration issues. This development is discussed in greater detail in Chapter 5, but a main goal of the Systems Engineers is to act in an integrative capacity on the engine program management teams.

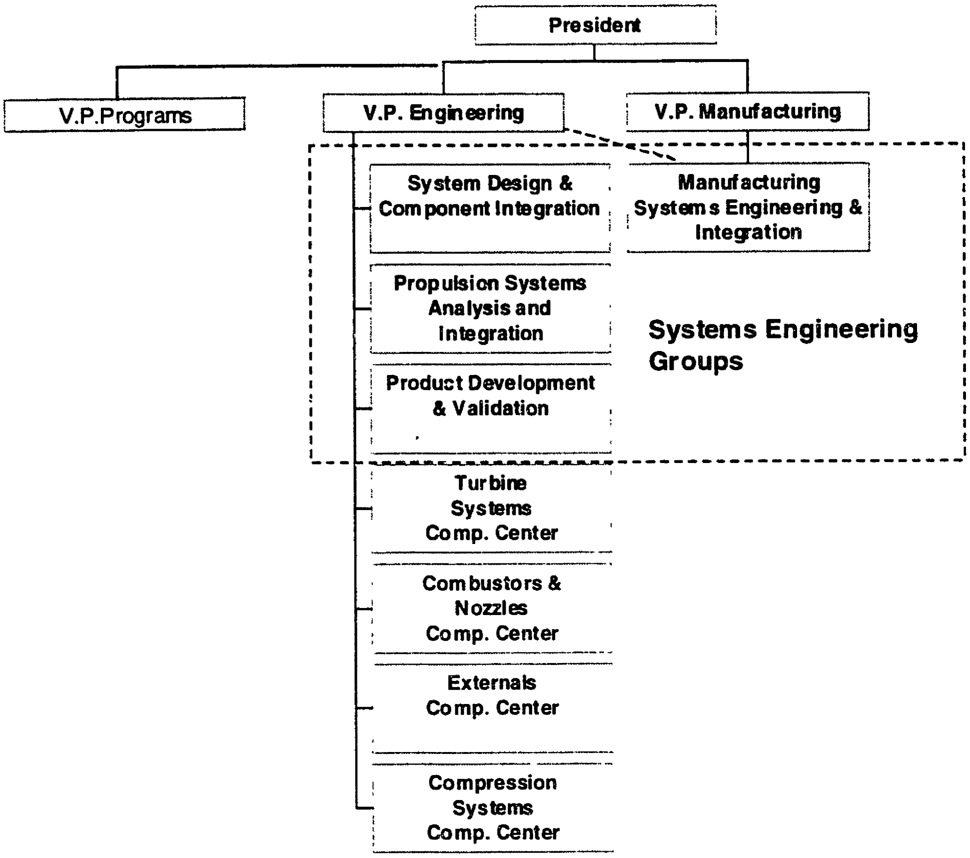

Figure 2-3
Addition of Systems Engineering Groups to the Component Center Structure

2.3.5 Module Center Concept (Future)

In an effort to further improve the design process and leverage their assets at the manufacturing sites P&W management announced a shift to the Module Center structure in the Fall of 1998, with implementation to commence immediately. The Module Centers are responsible for the overall design and manufacture of each component. There are four primary Module Centers that have hardware design and manufacturing responsibility:

Compression Systems Module Center, Middletown, CT
Fan, Low Pressure Compressor, High Pressure Compressor components and associated hardware.

Turbine Systems Module Center, North Haven CT
High Pressure Turbine, Low Pressure Turbine components and associated hardware.

Combustors/Augmentors/Nozzles Module Center, E. Hartford, CT
Diffuser/Combustor component and associated hardware.

Externals and Nacelles Module Center, Middletown, CT
Engine Externals and Controls.

One characteristic is that engineering will be co-located to the manufacturing sites along with detailed hardware design responsibility. A downside to this movement is further risk of duplication of engineering effort since several engineering organizations will be established. In addition, there will potentially be a loss of systems integration ability since the component teams will no longer be co-located.

Characteristics of the Module Center

- Component focus
- All functional expertise necessary for the design, development, production of the hardware co-located in the module center
- Design and build responsibility resides in the Module Center

Expected benefits of this structure:

- Cross training
- Rotation
- Same metrics
- DFX (Design for Cost, Manufacturing, Assembly, etc.)
- Lower cost designs
- Specialized and efficient processes developed at each center

Potential risks associated with this structure

- Dilution of functional expertise;
- Component optimization at the expense of system sub-optimization;
- Non-standard processes developed at each enter;
- Production push will drive poor engineering decisions;
- Loss of systems integration, as the co-located component teams are distributed geographically to the Module Centers. Formal and informal communications between component teams becomes more difficult.

In order to reduce the potential risks, the Systems Engineers will have to step up, especially in regards to the system integration issues. In the future, engineering and manufacturing will be integrated and organized around the Component/Module. Design Engineering folks from the existing Component Centers will be moved into the Manufacturing facilities. The Manufacturing facilities will focus on Component Production rather that Part-Families. The a) integration of Engineering with Manufacturing; and b) the Change in focus to Component as the product at each manufacturing facility constitutes the change to Module Centers.

2.4 Summary

This chapter reviewed the evolution of the product development and manufacturing organizational at P&W over the past 8-10 years. Table 2-4 outlines the characteristics of each organization, showing the types of activities that were centralized, and therefore presumably easier to manage, activities or groups that were distributed and presumably more difficult to manage and coordinate their activities, and a note on the "unit of focus" in both the Design Engineering Community and the Manufacturing community. Note that with the advent of the Module Center, both Design Engineering and Manufacturing will be focusing on the same unit: the engine module.

The table highlights the fact that as P&W moves to the Module Center structure, Systems Integration activities will become more of a challenge because the various Component teams will be distributed geographically at the different manufacturing sites. In Chapters 4, and 5, we will investigate the system design process and the Systems Engineering Process with the intent of making recommendations in Chapter 6 about how the Systems Engineers can insure that the Systems Integration issues get the proper visibility and attention to ensure a successful engine design. We will first investigate various tools that may be used to understand these processes in the next chapter.

Table 2-4
Summary of P&W Organizational Changes 1990-1999

	Engineering					
Evolution of Organization	**Centralized Activities**	**Distributed Activities**	**Focus**	**Mfg. Focus**	**Eng./Mfg. Integration**	**System Integration Activity**
Functional (pre-1990)	Functional Groups	Engine Program Mgmt.	Functions / Disciplines	Mfg. Processes	None	Informal Processes. Lack of System Focus
IPD (1991)	Parts Teams, Program Mgmt.	Functional Groups	Part Design	Mfg. Processes	Little. Lack of Mfg. Resources for IPT participation	Informal Processes. Lack of System Focus
Component Centers (1993)	Component Teams, Program Mgmt.	Functional Groups	Component Design	Parts Families	Little. Lack of Mfg. Resources for IPT participation	Introduce some formal Processes with System focus.
Product Centers (1995)	Component Teams, Program Mgmt.	Functional Groups	Component Design	Parts Families	Partial. Pockets of good Mfg. IPT participation.	Introduce more System focused Processes
Systems Engineers (1997)	Component Teams, Programs Mgmt., Functional Groups		Component Design	Parts Families	Partial. Pockets of good Mfg. IPT participation.	Formal Systems Engineering Process Developed
Module Centers (1999)	Program Mgmt., Functional Groups	Systems Integration, Component Design & Mfg of Modules	Design & Manufacture of Modules	Modules	Complete. Co-location of Mfg. And Design Engineering	Moderate within Module, weak across Modules

Chapter 3

Techniques for Modeling a Design Process

The process of large-scale product development involves the activities of multiple integrated product teams (IPT). The work of each team is impacted by and impacts the work of other teams involved in the development process. This coupling amongst teams is one of the characteristics that make the process complex and is what leads to difficulty in managing and improving the product development process as a whole. Although IPTs work well for small projects, application to development of large complex products is more of a challenge because of the number of people and teams involved. Communications must be facilitated between many teams in order to properly integrate their individual efforts.

There are many process management tools available to the design manager that allow various levels of control over the product development process. Many of these have gained and lost popularity through the reengineering wave that struck organizations in the early 1990s, some being more useful than others and some are more applicable to problem analysis and improvement of the product development process. The reason we model the design process is to identify ways of improving the speed of the process and quality of the product that results from it by identifying areas that generate rework, and developing solutions that can be used to reduce design iterations, for example, by reengineering the process (resequencing tasks, defining new tasks, deleting old tasks, etc.), providing new engineering automation tools (CAE, CAD, CAM), or reassigning tasks.[4] The assumption is that a more efficient product development process will result from a clearer, more accurate, more responsive and more timely information flow, and that this flow must first be defined, then managed.

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[4] Smith, R.P., Eppinger, S. D., "Identifying Controlling Features of Engineering Design Iteration," *Management Science*, Vol. 43, No. 3, March 1997, pp 276-293.

The remainder of this chapter will provide a review of existing tools and techniques useful for modeling the design process. We then settle on the Design Structure Matrix as the tool to be applied in this thesis to explicitly document the complex interactions and interdependencies among the parameters that drive the aero-engine development process. Our intent is to use these interactions to identify areas in which the Systems Engineers must focus their attention because of the likelihood of inter-component conflicts due to the coupling of parameter dependencies across two or more components.

3.1 Conventional Tools (Flow Charts, Gantt Charts)

Project management tools exist that are useful in developing schedules for coupled design activities that can be characterized by precedence relationships. Flow Charts are good for highlighting the path of a job through a process and the associated milestones. They can convey a sequence of steps well and known information loops are easily shown as two-way information flow between tasks. Subtle feedback loops are not easily represented, e.g. if a task only rarely affected an upstream task, the link between the tasks may be omitted. A Gantt chart will typically depict relative start-finish times of tasks and can capture precedence information, i.e. what tasks must be completed before another task may begin. The critical path is identified but the informational needs of tasks are not explicitly captured.

Directed Graph

One method for modeling the product development process is the Directed Graph. In a *digraph* the design activity is represented by nodes which represent sub-tasks connected by arcs which represent directed information flow. The *digraph* is most popular for showing the precedence relationships among tasks in a project or parameters in a design. It is typically difficult to discern the underlying structure of the design process from a *digraph*, especially when the process becomes complex and has many nodes and arcs.

Consider two design tasks A and B. Figure 3-1 shows a digraph of three possible ways the tasks can be related.[5] Figure 3-1(a) shows that A and B must be executed in series, since B relies on

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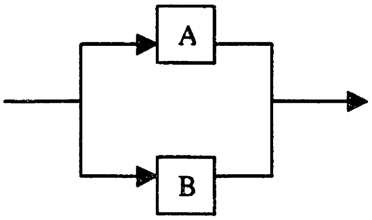
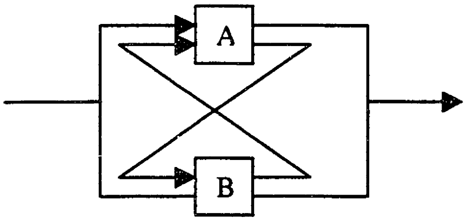
[5] The following discussion is modified from Eppinger, S.D., "Model-based Approaches to Managing Concurrent Engineering," *Journal of Engineering Design*, Vol. 2, No. 4, 1991, pp 283-290.

input from A. In Figure 3-1(b), A and B are independent from one another, and may be executed in parallel. In Figure 3.1(c), the tasks are coupled and rely on each other for proper completion. The coordination of the series and parallel tasks is straight forward, whereas the coupled tasks are more difficult to organize, requiring more design time and iteration to finalize.

a) Dependent Tasks



(b) Independent Tasks (Parallel)



c) Interdependent Tasks (Coupled)

Figure 3-1
Possible Task Relationships

Program Evaluation and Review Technique (PERT)

PERT is a modeling tool in which the nodes of the digraph are arranged in order along a time line. In a slight modification, the PERT model tasks are placed along the arcs between the nodes and nodes represent task completion milestones. The length of an arc is typically proportional to the duration of the task it represents. PERT models are useful for calculating the critical path on a project. A major deficiency in this modeling process is the lack of feedback loops indicating iteration in the design process.

PERT charts do not capture coupling of tasks, and the iterative nature of design work. The PERT chart typically depicts a series of parallel and series tasks and parameter dependencies, but since an understanding of the causes of iteration in the design process is key to reducing rework and making the process more efficient, PERT is not an effective tool for modeling the process, especially if the goal is to eliminate iteration. GERT (General Evaluation and Review Technique) is a modification of PERT which does capture iteration cycles in the process but Smith & Eppinger point out that as the system or process gets complex the GERT network is difficult to work with and other methods are used to analysis the system.[6]

Structured Analysis and Design Technique (SADT)

Structured Analysis and Design Technique is a process defined by Ross in which a system of interconnected boxes and arrows depict the input and output of information.[7] Rules for building the SADT document results in a more structured model that can represent feedback loops and iteration in the process. SADT uses a strict hierarchical top down approach to model a process, where the interrelations between model processes can only be described on the same level of detail. Unfortunately, real programs have various information dependencies and time dependencies between process steps.

IDEF (Integration Definition) was developed from SADT by the US government in support of Computer Integrated Manufacturing and Concurrent Engineering activities. But IDEF charts also tend to grow rapidly as the system becomes more complex. Gebala and Eppinger report that the Digraphs, PERT charts, and SADT documents are cumbersome to use, due to their physical size. Although they may be effective for documenting an existing or proposed design process they offer little by way of insight into the process that could guide an analyst to improve the process or effectively manage it.[8]

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[6] Smith, R.P., Eppinger, S. D., "Identifying Controlling Features of Engineering Design Iteration," *Management Science*, Vol. 43, No. 3, March 1997, p 278.

[7] Ross, D.T., "Structures Analysis (SA): A Language for Communicating Ideas," IEEE Transactions on Software Engineering, Vol. SE-3, No. 1, January 1977, pp16-34.

[8] Gebala, D.A., Eppinger, S.D., "Methods for Analyzing Design Procedures," Design Theory and Methodology ASME, DE-Vol. 31, 1991, pp 227-233.

3.2 Tools for Analysis and Improvement of the Product Development Process

For the reengineering of development processes or for its continuous improvement, the development process has to be modeled and documented. Due to the special nature of concurrent engineering processes, a method for process modeling has to be able to support and map the huge interconnectivity between the processes of different engineering disciplines over all hierarchies. The dominant elements in a model for concurrent engineering processes are the informational relations and flows between the different processes.[9]

Methods for Overlapping Design Activities

Krishnan, Eppinger, and Whitney[10] discuss the problem of reducing product development lead-time using an approach called iterative overlapping in which preliminary information is exchanged between tasks, rather than waiting until all information is finalized before passing to a downstream task.[11] The iterative overlapping method helps the design team decide the optimal point at which preliminary design information can be passed to a downstream operation, facilitating the concurrent design approach and resulting in reduced project lead time. The issue of "parameter interdependence" is explicitly addressed in that the authors recognize the inherent coupling of design parameters in all products. Krishnan, Eppinger, and Whitney further develop a methodology for overlapping activities in industrial product development processes, suggesting that the preferred method of accelerating the product development process is through the more frequent exchange of preliminary information from upstream to downstream activities, as opposed to the single exchange of finalized information that characterizes many development processes.[12] The benefits of overlapping are somewhat mitigated by the risk of increasing downstream task duration. The use of preliminary information that is subject to change as it evolves may cause subsequent design iterations. The authors discuss the concepts of evolution and sensitivity, useful for determining

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[9] Fricke, E., et al, "Modeling of Concurrent Engineering Processes for Integrated Systems Development," *Proceedings of the 17th Digital Avionics Systems Conference, Electronics in Motion*, Oct/Nov 1998, Bellevue, WA.

[10] Krishnan V., Eppinger S.D., and Whitney, D.E., "Accelerating Product Development by the Exchange of Preliminary Product Design Information," *Journal of Mechanical Design*, Vol. 117, December 1995, pp 491-497.

[11] Ibid, p 492.

[12] Krishnan V., Eppinger S.D., and Whitney, D.E., "A Model-Based Framework to Overlap Product Development Activities," *Management Science*, Vol. 43, No. 4, April 1997, pp 437-451.

which parts of the exchanged information to finalize early and which to use in a preliminary form. Application to car door and pager are used as illustrative examples of the overlap methodology.

"True simultaneous engineering involves a high coordination cost, inherently coupled tasks must often be executed sequential."[13] Clark and Fujimoto[14] observe that the use of cross-functional teams does not guarantee a successful product development process; the teams need to be tightly integrated and strongly coordinated. Gebala and Pekar[15] show that weakly coordinated IPTs can perform worse than functionally integrated teams. The authors consider the case of two firms developing a prototype product. Firm A recognized the tight coupling between three major components, designed the components simultaneously, requiring lengthy negotiations (5-10 design iterations, up to six months) before having enough detail to build the first working prototype. Firm B recognized coupling of all three components, but let two take precedence over the third, left the third design to last, and obtained a working prototype within a few weeks.[16]

Kusiak's work[17] in modeling the design process provides an interesting complement to the work of Eppinger, Whitney, Krishnan, and others discussed above. Most interesting is the proposed use of the incidence matrix to model the interdependencies between design parameters and design tasks. Kusiak proposes a method for decomposing the design process to enhance concurrency. Each task is driven by input parameters and produces output parameters. The objective is to decompose the design process into subtasks in such a manner that the interdependencies between sub-tasks are reduced. In this way concurrency in the design process can be enhanced resulting in shorter design lead-time.[18]

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[13] V. Krishnan, S.D. Eppinger, D. E. Whitney, "Ordering Cross-Functional Decision Making in Product Development," MIT Sloan School of Management, MIT Industrial Liaison Program, Report 2-43-93, 1993.

[14] Clark, K., and Fujimoto, T., "Product Development Performance: Strategy, Organization, and Management in the World Auto Industry," Harvard Business School Press, Boston 1991.

[15] Reported in V. Krishnan, S.D. Eppinger, D. E. Whitney, "Overlapping Product Development Activities by Analysis of Information Transfer Practice," MIT Sloan School of Management, MIT Industrial Liaison Program Report 2-44-93, 1993

[16] Ibid.

[17] See for example Belhe, U. and Kusiak, A., "Modeling Relationships Among Design Activities," *Transactions of the ASME*, Vol. 118, December 1996, pp 454-460.

[18] Kusiak, A., Wang, J., "Decomposition of the Design Process," *Journal of Mechanical Design*, Vol. 115, December 1993, pp 687-695.

Fricke, et al, from the Technische Universitat Munchen recently presented work at MIT related to their approach to analysis of the product development process, based on work in collaboration with BMW.[19] These researchers recognize the interdependence among design tasks and parameters. This paper is very interesting because of the independence of the researchers from the attempts made in the US to understand and model the product development process. These researchers reach many of the same conclusions reached by Eppinger, Whitney, Kusiak and others;

- The product development process is significantly different from other business processes
- The tasks and parameters that characterize any particular process or product can be unrelated, moderately related, or highly inter-related;
- A modeling methodology must be able to address the coupling amongst design tasks, and to handle the possibility of design iterations and information feedback that characterizes the development process.
- An analysis of the market reveals that there are no tools available commercially that meet the requirements of a proper product development process modeling tool.

It is clear from these papers that: a) there is great interest in understanding the structure of the product development process in order to optimize it, resulting in reduced design cycle times; b) the product development process is iterative by nature, and attempts to reduce cycle times by overlapping design activities (concurrent design practice) has the potential to increase the number of iteration of a particular activity due to the coupling of design parameters and tasks; c) a process for explicitly defining the parameter and activity interdependence in the product development process is necessary prior to attempting to overlap design activities.

3.3 Design Structure Matrices (DSM)

Engineering design involves the specification of many variables that together define a product, how it is made, and how it behaves. In order to design and develop a complex system, it is common practice to decompose the system into sub-components that are easily handled and then to re-integrate the sub-components into the Integrated System. The Design Structure Matrix has been demonstrated to be a powerful tool useful in helping engineering teams understand the design process of complex systems and to structure development flow and teams to increase design process efficiency. Manufacturing firms both large and small are struggling with ways to make their Product Development Process (PDP) leaner and more agile. At the core of the PDP are the challenges that make product development difficult: task coordination, task complexity, and task

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[19] Ibid., Fricke.

coupling. Many firms have turned to Integrated Product Development in the past decade in the hopes of solving their PDP inefficiencies. But Eppinger[20] suggests that concurrent engineering is more than just putting together the right team; it takes a complete re-thinking of the way a firm currently goes about the business of designing and producing their product. A major route to PDP improvement, other than making each task more efficient, is to resequence individual tasks or groups of tasks in the PDP so that required information is made available sooner and used sooner in the Integrated Product Development process[21]. An extension of this is to break existing tasks into parameters and recombine them into new tasks.

The Design Structure Matrix (DSM) is a tool that enables a vast improvement in the PDP by modeling the process, identifying critical information, and facilitating information exchange. It can also help alleviating some of the effects of three problems in concurrent engineering: iteration (solving coupled issues faster), overlapping (acceleration of sequential tasks), integration (coordination of parallel tasks). The value of the DSM comes from its ability to capture the complex interactions and interdependencies among tasks in a program/project and present them visually in a format that is easy to comprehend and present to others.

The DSM is a square matrix that is related to the "roof" on the House of Quality in Quality Functional Deployment.[22] Each row in the DSM represents a task in the PDP. Across the top of the DSM the columns are labeled with the same tasks. The elements of the DSM represent information dependencies amongst the tasks. Reading across that row shows information that the task depends upon to be completed. A mark in row *i* column *j* means that in order to complete task *i* we need information from task *j*. In a binary DSM, a mark above the diagonal means that information from task *j* is not known yet, so a guess must be made. Reading down column j shows the tasks *i* that task *j* supplies information to.

Recall the types of information flow depicted in Figure 3-1(a-c) when we discussed digraphs. The same types of information flow can be captured within the DSM as follows:

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[20] Eppinger, Steven D., "Three Concurrent Engineering Problems in Product Development," MIT Sloan School of Management, Presentation given to System and Project Management Class, September 26, 1997.

[21] Eppinger, Steven D., et al., "A Model-Based Method for Organizing Tasks in Product Development," *Research in Engineering Design*, Vol. 6, pp. 1-13, 1994.

(a) Dependent Tasks or Parameters [Refer to Figure 3-1(a) series]

	A	B
A	A	
B	X	B

(b) Independent Tasks or Parameters [Refer to Figure 3-1(b) Parallel]

	A	B
A	A	
B		B

(c) Interdependent Tasks or Parameters [Refer to Figure 3-1(c) coupled]

	A	B
A	A	X
B	X	B

The DSM is a very powerful tool for analysis of the design process because it can:

a) Provide an understanding of the flow of information in the system;
b) Determine the optimum number of teams in the PDP and determine team composition;
c) Suggest the optimum sequencing of tasks to reduce unintended iterations and rework in the PDP;
d) Identify critical areas for improvement based on the level of coupling amongst tasks and redefine critical tasks to facilitate project flow;
e) Expose constraints and conflicts in the product development process.

The DSM representation is compact which makes it practical for modeling complex projects in a matrix form and allows for computer analysis. Unlike PERT, DSM allows tasks to be coupled, explicitly drawing out the complex relationships between tasks and parameters in the development process. An example of a DSM is shown in Figure 3-2. An "x" in the matrix shows where two tasks or parameters interact, i.e. a flow of information. Reading across a row shows the tasks or parameters that feed information to the task/parameter in that row. Reading down a column reveals the tasks or parameters that the task in the column feeds information to. In the example in Figure

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[22] Clausing, D., and Hauser, J., "Quality Functional Deployment," Harvard Business Review, 1988.

3-2, Parameter D depends on information from parameters E, F, & L; Parameter B provides information to C, F, G, J, & K[23].

	A	B	C	D	E	F	G	H	I	J	K	L
A	A		X									
B		B										
C		X	C									
D				D	X	X						X
E					E	X		X			X	
F		X				F						X
G		X					G				X	
H	X			X				H	X		X	
I			X			X			I	X		
J		X	X			X				J	X	X
K		X	X								K	
L	X								X	X	X	L

Figure 3-2
Example of a Design Structure Matrix

3.4 Constructing the DSM

In order to construct the DSM, it is best to get input from engineers and their managers regarding the tasks in the PDP and the level of interaction for the information flow. For a task based approach, one might start with a list of the tasks of all the Integrated Product Teams involved in the PDP, and ask each team for input on the level of interaction between the teams. In a parameter based DSM, the rows and columns are the design parameters that drive the design or define the system. An effective research method has been to ask the engineers and managers involved in the

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[23] DSM Examples in Figures 3-2 and 3-3 are from Eppinger, S. D., "Model –based Approaches to Managing Concurrent Engineering," *Journal of Engineering Design*, Vol. 2, No. 4, 1991.

design activity to define precedence relationships between the parameters. That is, given a parameter A, what parameters B, C, ..., must be defined prior to final definition of A?

The greater challenge is the partitioning of the DSM (or resequencing) to draw out interesting relationships and couplings between the tasks and to optimize the flow of information.

3.5 Partitioning the DSM

The DSM will be used to depict the patterns of information flow in a project. It is necessary to have an accurate understanding of the important information to transfer between teams and the DSM method is often aimed at structuring complex design processes in order to optimize them and develop better products more quickly. The process of reordering the DSM is called partitioning. The goal is to resequence the design tasks to maximize the availability of information required at each stage of the design process; this can be accomplished by making the matrix lower triangular and/or creating square blocks on the diagonal. The strategy is to determine how to perform each task as early in the process as possible. When all information necessary for a task is available, the task is positioned first in the DSM. Such tasks are easily identified as those which have empty rows, except for the diagonal element. A task that provides no information to downstream tasks is placed at the end of the matrix. These tasks are identified as those which have empty columns, except for the diagonal element. For the remaining tasks which provide downstream information and/or require information input prior to being completed, there is a loop of information dependence. Loops can be identified by using a *Path Searching Method* or by *Powers if the Adjacency Matrix Method.*[24]

Partitioning the DSM will transform the matrix into lower triangular form, indicating a sequence of tasks or parameter definitions that flows from start to finish of the design process. Complete lower triangularity is rarely possible in real system design processes because of the coupling between tasks. In this case, block triangular form is attempted, such that blocks of highly coupled tasks or parameters lie on the diagonal of the DSM. The coupled blocks represent design iteration, with marks below the diagonal representing feed forward information flow, while marks above the

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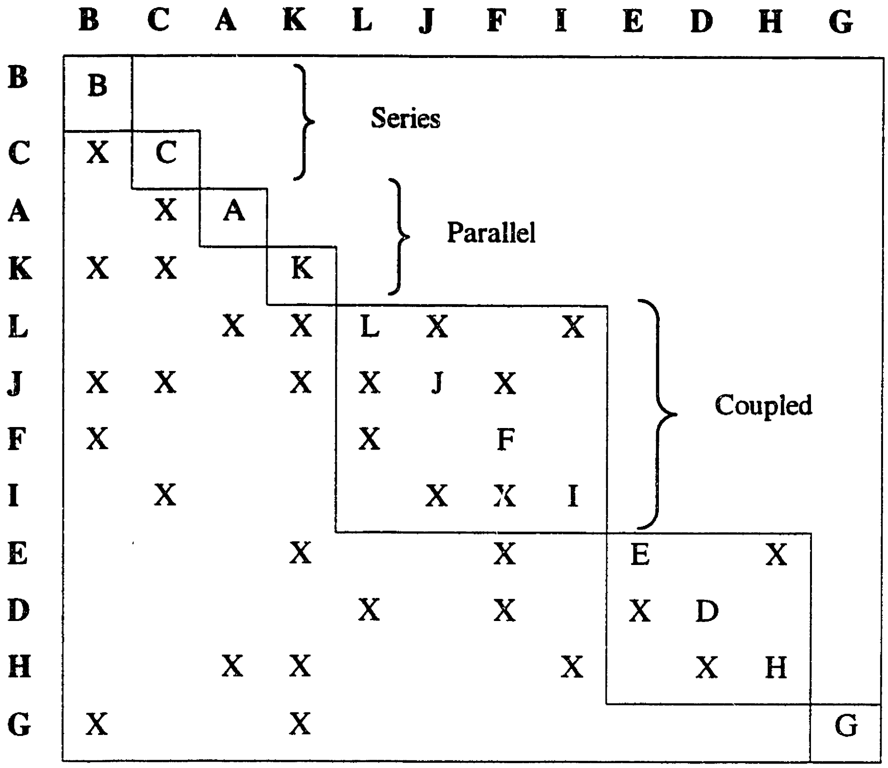
[24] Gebala, David A., and Eppinger, S. D., "Methods for Analyzing Design Procedures," *Design Theory and Methodology*, DE - Vol. 31, pp. 227-233, ASME 1991.

diagonal represent feedback loops and potential causes of rework. Figure 3-3 shows a view of the DSM from Figure 3-2 after it has been partitioned.



	B	C	A	K	L	J	F	I	E	D	H	G
B	B											
C	X	C										
A		X	A									
K	X	X		K								
L			X	X	L	X		X				
J	X	X		X	X	J	X					
F	X				X		F					
I		X				X	X	I				
E				X			X		E		X	
D					X		X		X	D		
H			X	X				X		X	H	
G	X			X								G

Figure 3-3
Partitioned Design Structure Matrix

Warfield[25] published an early paper of interest to DSM practitioners on the use of binary matrices and directed graphs (digraphs) to capture the information flow and parameter/task interdependencies in a general system structure. Eppinger references Warfield's work in his 1991 work on approaches to managing concurrent engineering projects.[26] Steward's work builds on Warfield's, suggesting techniques for building and sequencing the Design Structure Matrix in such a manner as to elucidate the types of parameter relations in a process and to characterize series, parallel, and coupled design tasks. The partitioning process can be difficult for large densely populated matrices. Several algorithms and heuristics have been developed to aid in the partitioning

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[25] Warfield, J. N., "Binary Matrices in System Modeling," *IEEE Transactions on Systems, Man, and Cybernetics*, Vol. SMC-3, No. 5, September 1973, pp 441-449.

task. If the objective is to minimize the interfaces between subsystems, the partitioned matrix will have clusters of elements along the diagonal, indicating the size and membership of sub-systems.

3.6 Chapter Summary

The system design process is inherently iterative and planning decisions have to be made about how to iterate and where to use estimates for design parameters in order to move the design process along. Several tools for capturing and displaying the product development process have been reviewed. Most conventional tools assume a sequential processes, and do not capture the iterative nature of most design processes, especially those associated with the development of large complex systems. Others adequately capture precedence information, i.e. Task A must occur before Task B, but these tools do not map the information flows in a process well, making improvement of the process difficult.

A matrix representation of the design process overcomes many of the deficiencies found in other modeling processes, especially size and complexity limitations and the lack of ability to capture design iterations and feedback/feed-forward loops that are a major part of design processes. The DSM is chosen as the tool for depicting and analyzing the design process in the remainder of this thesis because of its following strengths: a) ability to represent large complex systems and processes visually simplified format; b) ability to use computer to manipulate the DSM and draw out greater understanding of the underlying structure and interdependencies in the process or system under analysis. We will make extensive use of the DSM in the following chapters to characterize the Aero-engine development process, explicitly highlight system level design integration issues, and make recommendations to improve the proposed systems engineering process based upon an analysis of the aero-engine design process.

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[26] Eppinger, S.D., "Model-based Approaches to Managing Concurrent Engineering," *Journal of Engineering Design*, Vol.2, No. 4, 1991, pp 283-290.

Chapter 4

The Aero Engine Design Process

The modern gas turbine aero-engine is aptly described as a large complex system. It has a large number of parts, is technically sophisticated in terms of the product and the development, analytical, and manufacturing processes used to design and build the system, and involves several hundred people on tens of teams. The system architecture is modular and but the component sub-systems are highly coupled which requires close coordination of the development teams during the product development process. This chapter will begin with a brief review of some of the fundamentals that drive the design of a gas turbine engine. The remainder of Chapter 4 will cover the application of the Design Structure Matrix (DSM) presented in Chapter 3 to the individual engine components. The parameters that drive the design of each component will be identified and the DSM will be used as a tool to document the interdependencies among these parameters. More importantly, each DSM will identify what appear to be system level parameters that have interactions both inside a specific component and outside with the super-system (the engine).

Using this methodology it will be shown that much of the component design work can in fact be done by integrated development teams working somewhat independently from the other teams, once the high level system requirements have been flowed down into component requirements. But there are significant interactions that occur outside of the limited scope of the component design team that the team and the Systems Engineers must be aware of at all times in order to ensure an optimal system design. The DSM will be used to identify these "extra-component" design issues.

This chapter will conclude with the integration of all the component DSMs into an engine system level DSM which explicitly identifies areas of parameter interaction amongst all the engine components. These are the interactions that the Systems Engineers will manage during all phases of the engine life cycle, from concept generation through field service and retirement of the product. In Chapter 6 the aero-engine design process will be linked to the Systems Engineering process by mapping the design parameters to tasks in the Systems Engineering Process.

4.1. Principles of Aero Engine Operation – Turbomachinery Fundamentals[27]

In this section a general discussion of the operation of a gas turbine aero-engine is provided. Commercial and military aero engines are very similar in their components and operation, but derive their thrust from different mechanisms:

- **Turbo-Jet** engines derive their thrust from the jet of exhaust exiting the engine core at the rear of the engine;
- **Turbo-Fan** engines derive their thrust from a combination of by-pass flow (i.e. the portion of flow that does not pass through the engine core) and exhaust jet;
- **High By-Pass Turbo-Fan** engines having large diameter Fans that provide the majority of the overall thrust produced by the system. Most of the incoming flow does not pass through the core of the engine; it instead bypasses the engine core to directly produce thrust.

Most modern commercial engines are of the High By-Pass Turbo-Fan variety because they are inherently more fuel-efficient. This chapter and the remainder of the thesis will focus on commercial rather than military power-plants, although the analysis techniques and lessons learned are largely applicable to both types of engines.

The purpose of an aircraft gas turbine engine is to generate a propulsive force greater than the drag forces associated with the aircraft and propulsion system combination. Fundamentally, there are three main functions, which enable an aero engine to produce propulsive thrust: compression, combustion, and expansion. Each of these functions is discussed below along with the engine components that fulfill the functional requirements.

4.1.1 Compression

Figure 4-1 shows the basic cross-section of a gas turbine engine. Air enters the engine at the left of the figure, and passes first through the Fan. The Fan serves two functions. The first is to induct an air flow into the engine; a portion of that air will be compressed, burned, and exhausted to power the engine. The second function is to accelerate a large volume of air to produce propulsive thrust. About 15% of the flow that passes through the Fan becomes "core flow" and is passed through the core of the engine. The other 85% of the flow is called "By-Pass" air, and it produces about 90% of the total thrust of the engine.

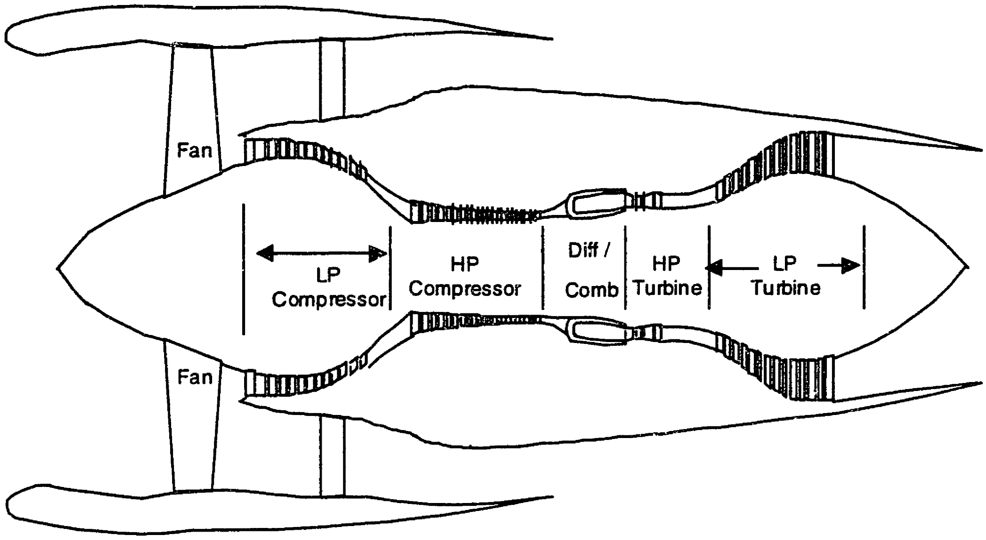

Figure 4-1
Typical High By-Pass Fan Cross Section

The Compressors decelerate the core flow and raise it in pressure; there is also an associated temperature rise. A typical P&W commercial engine has two compressors, the Low Pressure Compressor (LPC) and the High Pressure Compressor (HPC).

The core flow first passes through the LPC whose job it is to take engine core flow air from the Fan and start the compression process. The LPC has a number of stages[28] of airfoils, each stage serving to incrementally decrease the velocity and increase the pressure of the flow. The last component in the compression process is the HPC which serves to further decrease the velocity of

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[27] A good portion of this section on the operation and design of the engine to taken from "Advanced Engine Programs System Analysis & Integration – New Hire Training Program", internal P&W documentation, unpublished, 1998.

[28] A stage in a compressor is defined as a row of rotating blades followed by a row of stationary stator vanes. A turbine stage is conventionally defined as a row of stationary stator vanes followed by a row of rotating turbine blades.

the engine core flow and increase its pressure. Typically, the pressure rise over the length of the HPC is much greater than over the LPC length and the flow reaches its highest pressure level in the engine at the exit of the HPC.

To summarize, the compression system of the commercial High By-Pass Fan gas turbine engine is comprised of three components, the Fan, LPC, and HPC. The Fan provides core flow to the engine, flow that passes through the LPC and HPC to be raised in pressure and temperature and decelerated in preparation for the combustion process. The large portion of the flow through the Fan that bypasses the engine core provides the majority of the thrust generated by a high by-pass fan engine.

4.1.2 Combustion

Once the engine core flow has been sufficiently compressed in the axial flow LPC and HPC, it passes to the Diffuser. The diffuser section of the engine commences the rapid expansion of the flow, preparing it for combustion in the Combustor. In the Combustor, fuel is added to the flow and burned, greatly increasing the temperature of the flow, and causing it to accelerate through the turbine section. In the following analyses of the engine, the Diffuser/Combustor will be treated as one component.

4.1.3 Expansion

The whole principle of turbo-machinery is predicated on the assumption that we can take an air-flow, add energy to the flow by compressing the gas and adding fuel, release the energy through a combustion process, and efficiently extract the energy using a turbine. If we can extract the energy efficiently enough, there is enough energy to drive the compressors to feed the turbines, and excess energy available to do some useful work, i.e., drive the Fan so it can produce propulsive thrust.

The High Pressure Turbine (HPT) is the first component aft of the combustor, and receives the highest temperature, highest velocity flow as the gas rushes out of the combustor. The HPT extracts energy from the flow to directly drive the HPC (the HPC and HPT are connected by a short shaft). The HPT is followed by the Low Pressure Turbine (LPT), whose job it is to extract energy for the flow to drive the LPC and Fan.

In some direct or indirect manner, each of these components is related to all the others in a relatively short number of steps, and each clearly contributes to the successful attainment of overall propulsion system Cost, Weight, and Performance goals. The relationship from one component to another can be characterized by the type of information shared between the pair: mechanical interface/spatial adjacency, or a transfer of energy, material, or information. The coordination of the development of these components and systems can be a daunting task, but one that has been accomplished repeatedly and successfully for many propulsion systems over many years.

4.2. Aero Engine Design Process

The gas turbine aero-engine is a very complex piece of machinery. It has 4400 unique part numbers, 60000 parts, and produces up to 100,000lbs thrust. Metal temperatures in the hot section (Combustor, HPT, and LPT) can exceed 2000°F, and gas path temperatures may exceed 3000°F. The customer requires on-time delivery and low cost of ownership. This translates into low cost spares, long life hardware, ease of maintenance, and extremely high reliability.

What drives modern gas turbine design? The need for more power (thrust) to power larger aircraft. The second big driver is the push for ever more efficient engines. The limits on the design capability are: temperature, size/weight/cost, aerodynamic and thermodynamic limits, noise and emissions limits, and the limitations of the aircraft installation. The preliminary engine design process is comprised of a series of trades among these drivers.

The engine design process starts with what is referred to as cycle selection (because the parameters that will define the thermodynamic cycle are defined during this process). The primary objective in cycle definition is to minimize engine fuel consumption. For any given flight condition (altitude, ambient temperature, flight speed) optimizing the overall efficiency of the propulsion system will minimize Total Specific Fuel Consumption (TSFC, a measure of fuel efficiency). Overall efficiency is defined as the product of thermal efficiency (efficiency of converting chemical energy available in fuel into available propulsive energy) and propulsive efficiency (efficiency of converting available energy for propulsion into thrust).

The entire cycle selection process boils down to making trades among the various parameters that define the operation of the engine. Some of these important parameters are:

- Overall Pressure Ratio (OPR): the ratio of the maximum pressure reached in the engine and the ambient pressure at engine inlet.
- Combustor Exit Temperature (CET): the temperature of the gas flow as it leaves the combustor section of the engine and enters the turbine. This parameter is also referred to as T4 because the combustor exit is designated as station 4 in the engine.
- Fan Pressure Ratio (FPR): a measure of the gas pressure change across the fan stage of the engine.
- Total Specific Fuel Consumption (TSFC): a measure of engine fuel burn; analogous to automobile miles-per-gallon.
- By-Pass Ratio (BPR): a measure of the amount of total Fan flow that bypasses the engine core.
- Low Rotor Speed (N1): speed in revolutions-per-minute, of the low speed spool (Fan, LPC, and LPT).
- Et cetera. A list of the design parameters considered in this thesis is provided in a table in Appendix A.

For example, an increase in By-Pass Ratio improves the propulsive efficiency of the system, and results in a lower Low Rotor Speed (N1). But a lower Low Rotor Speed will result in a reduction in Low Pressure Turbine Efficiency, which in turn negatively impacts the Thermal Efficiency of the system causing a net increase in fuel burn. Therefore, any change in By-Pass Ratio must be balanced with a change in the Low Pressure Turbine (and most likely other components) as well.

4.3 Design Structure Matrix (DSM) Analysis of the Process

In this section the DSM is applied as a tool to organize design parameters at the conceptual design phase of engine development. This method enables the manger to look at the design process from a systems perspective in order to understand the design complexity caused by the interaction of the design parameters with one another. The DSM uses the information flow in the design process to identify these interactions. By analyzing the information flows related to component interrelationships, we can obtain an efficient development process.

We examine seven of the major components of the High By-Pass Turbo-Fan engine. Notably missing are evaluations of some major subsystems, for example Nacelles, Externals, and Controls. The timing of this thesis required that the scope of the investigation be somewhat limited. It is not the intent of the author to imply that a sub-system missing from this analysis is less critical than the sub-systems that are included. Future work may include pieces missing from this investigation.

It was our intention to capture as many of the important parameter interactions as possible in this analysis. The parameters used were compiled from P&W internal and external engine design documentation, and interviews with engine design experts, especially those with knowledge of the conceptual design process. It is possible that an important parameter is missing, in which case important interactions and dependencies will not be captured in this analysis. The author made every effort to avoid this.

The DSM application in this section involves four steps: (1) decomposing the engine system into components; (2) documenting the dominant parameters the drive the design of these components; (3) documenting the interactions between the parameters; (4) clustering the matrix elements to derive an understanding of the system level drivers. As outlined in Chapter 3, manipulating the DSM can provide new insight into the system decomposition and the interfacing between the components. For example, it is useful from a system design and organizational design perspective to understand the relationships between design parameters, which interactions occur within a specific component, and which interactions cross the component boundaries.

The first step in building the DSM, decomposing the engine system, first into modules (Compression, Diffuser/Combustor, Turbine, and External Modules), then into components, was completed before the start of this thesis. The partitioning of the system into the components defined in previous sections is standard throughout the gas turbine industry. The second step in the process, creation of an exhaustive list of parameters that drive the design of the various engine components, was not complete, and this was the starting point for the following analysis. The parameter list was established through:

- Examination of Internal Training material, both published and un-published (e.g. Component Integrated Product Team Training Module IV Documentation and Advanced Engine Programs New Hire training manual);
- Interviews and informal Discussions with internal experts about the process;
- The author's personal knowledge of the system design process;
- Process Re-engineering materials developed internally at P&W.

Once a list of parameters for each component was created, it was passed back to experts at P&W to get feedback and agreement that the lists were as complete as practicable. The next step in the DSM building process was to document the *precedence relationships* between parameters that drive the component design. Precedence Relationships for a specific parameter "A" define those parameters that must be defined prior to final definition of "A". The same sources of information that were used to create the initial parameters list were used to document the precedence relationships, and internal experts were allowed to review and comment/correct/add/delete relationships as they saw fit. Tables in Appendix A show the resulting precedence data for each engine component.

General Note: Appendix A contains the precedence information for each the components described in the following sections. Appendix B contains the Design Structure Matrices for each component.

4.3.1 Fan

The creation of the DSM for the Fan component (as well as all the other engine components) was straightforward. All the parameters that were identified as having some influence over the design of the Fan were placed horizontally and vertically along the left and top edges of a square matrix. For each row, the question is asked "what information must be known to determine or begin to determine this parameter?" A mark '1' was placed in every column relating to precedence information for this parameter (gathered from documents and experts as previously described). The precedence information for the Fan can be found in Appendix A on table A-1.

The columns of the DSM can be considered the "from" parameters and the rows the "to" parameters. Therefore, in reading the initial unsequenced DSM for the Fan in Appendix B, Figure B-1, we can read that "Fan Efficiency" is a function of the following parameters: Fan Airfoil Design, Fan Gap-to-Chord Ratio, Fan Operability/Surge requirements, Fan Tip Speed, Propulsive Efficiency, and Specific Flow.

The DSM shown in Figure B-1 is of the unsequenced matrix; parameters are simply listed alphabetically for the most part. Coupling between parameters can be envisioned, but in its current form, the DSM does not provide considerable insight into the Fan design process dependencies. The DSM can be partitioned to place the parameters in temporal order in which each parameter can be determined based on the definition of preceding parameters. In effect we are trying to make the matrix take a lower triangular form. By partitioning the DSM, feedback loops can be identified.

The DSM can be partitioned into two distinct regions. The first region is one in which the design is sequential or parallel; the second in which the design is coupled or iterative in nature, characterized by feedback loops. Figure B-2 shows the partitioned DSM for the Fan component. The algorithm identifies three main blocks in the design. In the first block ("High-Low Spool Work Split" through "T4") identifies parameters that "feed" the main design work for the component. These parameters are interpreted as input parameters. In order to proceed with the design of the Fan, we must either have these parameters defined or understand them as requirements or constraints on the parameters that define the Fan..

The second set of parameters ("Propulsive Efficiency" through "Noise") form a very highly coupled block in the center region of the DSM. These parameters are the main parameters that drive the Fan design. The "1s" in the columns to the left of the block indicate that these parameters take input from the parameters shown in the first block described above. The sequence of the parameters in this central coupled block is such that most of the "1s" lie below the diagonal. The implication is that this would be a good order for defining the parameters in order to reduce the amount of rework in the design process. Some marks remain above the diagonal indicating that a tentative value would have to be assigned to that parameter in order to proceed with the design. Once downstream parameters are defined this tentative value may be changed, based on the new information. For example, "Propulsive Efficiency" and "By-Pass Ratio" are coupled parameters. A value for "Propulsive Efficiency" may initially be set by assuming a value for "By-Pass Ratio", but that value may have to be changed as the Fan design progresses and "By-Pass Ratio" changes.

The third and final set of parameters in the Fan DSM are those that are most strongly *influenced by* the Fan design, but are associated with other engine components. For example system level parameters "Maintenance Cost" and "Production Cost" are driven by the component specific parameter "Fan Airfoil Design". It is also interesting to note that the DSM captures the interaction of Fan specific parameters that influence the Low Pressure Compressor, High Pressure Compressor, High Pressure Turbine, and Low Pressure Turbine

These "extra-component" interactions are indicative of the cross component interactions that are expected in the gas turbine aero-engine design. These are the interactions that are of interest to the Systems Engineers and must be managed by the Systems Engineering Process, especially in a distributed engineering and manufacturing environment.

4.3.2 LPC

The creation of the DSM for the LPC component proceeded in a manner similar to that of the Fan described in Section 4.3.1. The precedence information for the LPC can be found in Appendix A on Table A-2. The initial unsequenced DSM for the LPC can be found in Appendix B, Figure B-3, and the partitioned DSM is shown in Figure B-4.

It is interesting that a number of High Pressure Compressor design parameters show up as inputs into the LPC design process (see the upper left hand block of the partitioned DSM in Figure B-4). Some of the interconnectivity is caused by the LPC design dependence upon the "High-Low Spool Work Split". This parameter defines how much of the overall compression work is done by the LPC and how much is done by the HPC. For example, consider the case in which the system requirement is for an overall pressure rise across the LPC and HPC of 20:1. Let's also assume that the HPC pressure ratio is set at 10:1. This means the LPC will need to provide a pressure rise of 2:1 in order to meet the system requirement of 20:1. If the HPC pressure ratio is changed to 5:1, the LPC must now provide a pressure rise of 4:1 in order for the 20:1 ratio to be met. It should not come as a surprise that the 2:1 LPC design will be considerably different from the 4:1 LPC design. The coupling is captured in the "High-Low Spool Work Split" parameter.

The reader may note that "High-Low Spool Work Split" is a parameter that is defined early in the design process, during Conceptual and Preliminary Design Phases. It is an example of the type of parameter that may change as more detailed design work is completed. For example, as the design of the LPC matures, it may become apparent that the target value for "High-Low Spool Work Split" is infeasible, possibly due to inability to meet a performance requirement, necessary engine speeds, etc. In such an instance the work split parameter may be changed, resulting in some constraint relief in the LPC, but potentially causing a design constraint violation in the HPC, or vice versa.

4.3.3 HPC

The creation of the DSM for the HPC component proceeded in a manner similar to that of the Fan described in Section 4.2.1. The precedence information for the HPC can be found in Appendix A on Table A-3. The initial unsequenced DSM for the HPC can be found in Appendix B, Figure B-5, and the partitioned DSM is shown in Figure B-6.

The DSM shows that the High Pressure Compressor design is influenced by the High Pressure Turbine design parameters. This can be seen by noticing the HPT parameters (HPT efficiency, HPT expansion ratio, HPT stage count, and HPT velocity ratio) that show up as inputs into the HPC design process (see the upper left hand block of the partitioned DSM in Figure B-6). This finding makes sense – the HPC and HPT are mechanically coupled via a shaft running between the two components and the sole purpose of the HPT is to drive the HPC by extracting energy from the Combustor exhaust flow.

4.3.4 Diffuser/Combustor

The precedence information for the Diffuser/Combustor can be found in Appendix A on Table A-4. The initial unsequenced DSM for the Diffuser/Combustor can be found in Appendix B, Figure B-7, and the partitioned DSM is shown in Figure B-8. Note that this component appears to be more *driven by* the design of other components, as opposed to *driving* the design of others.

The DSM in Appendix B Figure B-8 shows that the Diffuser/Combustor section is in some ways driven by the HPC design, but takes the majority of its input from high level system parameters such as High Rotor Speed, Overall Pressure Ratio, and Total Flow. It is rather surprising that the Diffuser/Combustor is not more driven by HPT design parameters; in fact, the HPT parameters are not explicitly present in the DSM. This may not be out of line, considering that the engine operation is fundamentally defined by its cycle: Overall Pressure Ratio, By-Pass Ratio, and T4 (i.e. Combustor Exit Temperature). The Combustor provides the T4-combustor exit temperature, independent of the HPT, so we should not expect to see dependencies arise in the DSM (T4 and the other parameters are targeted at the "Design Point", a set of conditions that define a nominal engine operating condition and ignoring deterioration effects that come into play during engine field operation).

4.3.5 HPT

The precedence information for the High Pressure Turbine can be found in Appendix A on Table A-5. The initial unsequenced DSM for the HPT can be found in Appendix B, Figure B-9, and the partitioned DSM is shown in Figure B-10. The DSM shows that the HPT design is dependent upon system level parameters such as By-Pass Ratio and Development Cost (which often limits the turbine blade cooling and materials technologies that might be incorporated into a new design). There are low-spool design parameters that influence the HPT design, which may seem unusual until one considers that the diameter of Low Spool Shaft that passes through the HPT determines the allowable size envelop for the HPT disks. A constraint of HPT disk size places a constraint on High Rotor Speed, HPT blade design, and multitude other parameters in the HPC and HPC.

4.3.6 LPT

The precedence information for the Low Pressure Turbine can be found in Appendix A on Table A-6. The initial unsequenced DSM for the LPT can be found in Appendix B, Figure B-11, and the partitioned DSM is shown in Figure B-12.

Note that the design of the Low Spool Shaft that connects the Low Pressure Compressor to the Low Pressure Turbine is considered the responsibility of the Low Pressure Turbine design team. Parameters associated with the shaft design show up in the LPT DSM for this reason. These parameters include HPC and HPT length which influence the overall length of the shaft. Shaft length is one of the inputs into the Shaft Critical Speed analysis which determines the dynamic structural stability of the shaft throughout the engine operating speed range.

4.3.7 Mechanical Components

Mechanical Components mainly refers to the bearings and seals systems used in the gas turbine engine. Because of the complexity and criticality of this hardware in an aero-engine, it is considered its own component. The precedence information for the Mechanical Components can be found in Appendix A on Table A-7. The initial unsequenced DSM for Mechanical Components can be found in Appendix B, Figure B-13, and the partitioned DSM is shown in Figure B-14.

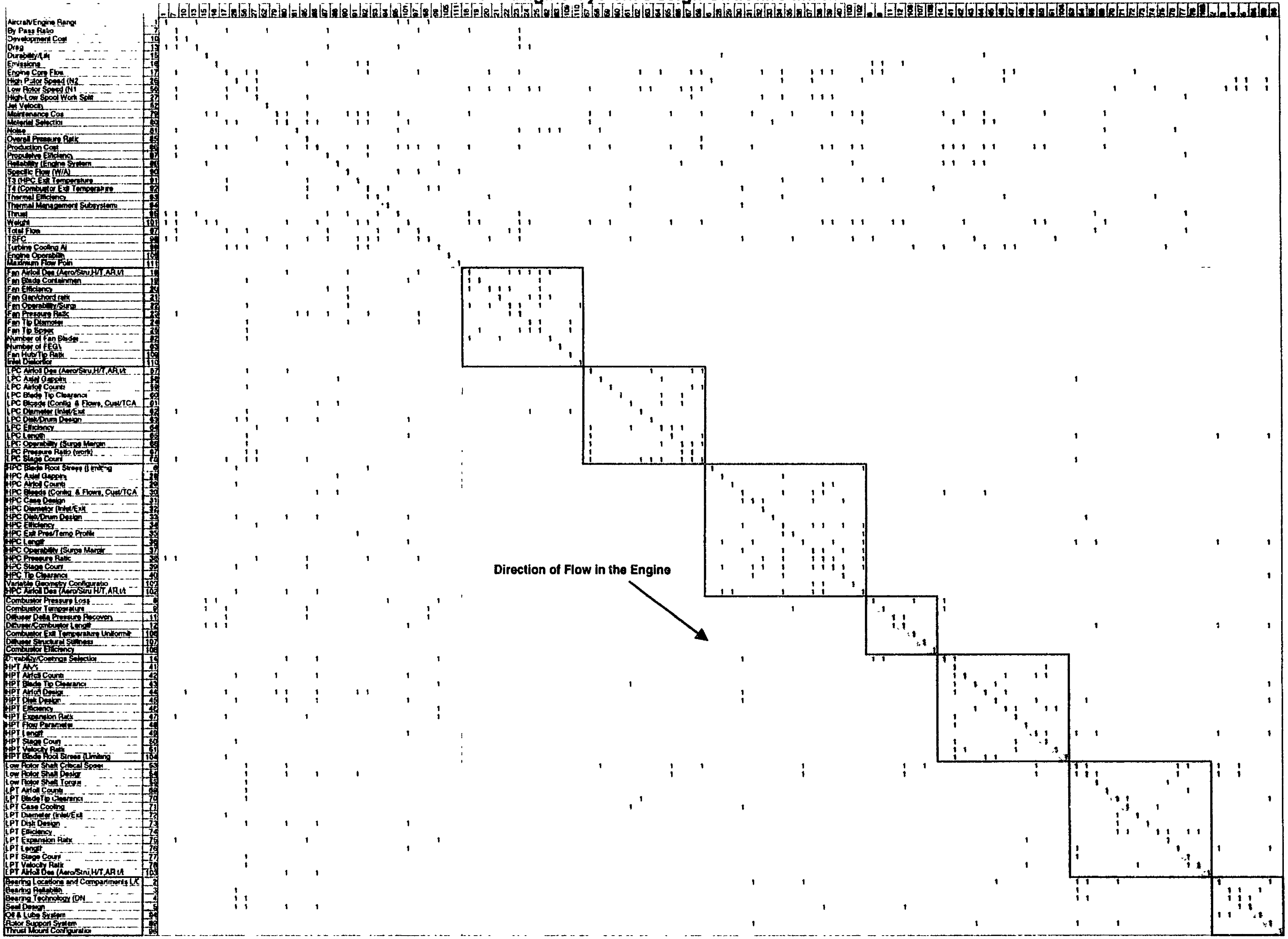
4.4 Identification of Inter-Component Communications

The Design Structure Matrices for each component add to our understanding of the flow of information in the engine design process. Each DSM has been shown to be comprised of three main blocks. The first block of parameters is considered input parameters that provide information, identify requirements, or impose constraints on the design of the component. The second block of parameters residing in a central region of the DSM is seen to be highly coupled, with significant interactions between parameters and the need to "guess" at upstream parameter values in order to make a decision concerning a downstream parameter. The third block of parameters is interpreted as those parameters that are influenced by the design of the particular component in question, and are important parameters that drive the design of other components in the engine design.

One of the goals of this investigation is to be able to identify the "System Level" parameter interactions. In this section, we compile all of the precedence information and all of the parameter interactions in an attempt to understand the overall system design issues amongst the components. The resulting DSM is shown in Figure 4-2. The design parameters have been grouped by component with system level components clustered into the left hand columns and across the top rows of the DSM. The System Level DSM shows that there is a set of parameters ("Aircraft/Engine Range" through "Maximum Flow Point" in this case) that significantly influences the design of all the engine components by flowing information to the parameters that drive the component designs. One may also observe that these system level parameters are influenced by the individual component designs; this is indicated by the numerous marks in columns across the top of the DSM.

One will also notice the relatively small amount of coupling between the engine components, aside from that which occurs through the system level design parameters. The component designs can be de-coupled by defining target values for the system level design parameters. Once the component requirements have been defined based on these target values, the component teams can indeed work in relative isolation on their designs at the Module Centers.

Figure 4-2
Aero-Engine System Design Structure Matrix



This result implies that the proper definition of the System Requirements and Component Requirements is the key to the success of a distributed design and development effort. The definition of the System Requirements and the Component Requirements during the Conceptual Design and Preliminary Design phases becomes one of the most critically important tasks in the engine design process. The DSMs show that all the component designs are coupled through system level design parameters. Conceptual and Preliminary Design is a highly iterative process in which performance, weight, cost trades are continuously made between components. The DSM indicates that this phase should not be completed by distributed teams. Even in the Module Center structure, representatives from the component teams should be co-located with the Systems Engineers and the Advanced Engine Program analysts to define the target values for the system level parameters, and to derive the System Requirements and Component Requirements.

The result of this interpretation is that the Systems Engineers must keep very close tabs on the evolution of the component designs and track the impact on the system level parameters very carefully. On the one hand, this analysis says that dispersing the engineering design teams to the Module Centers can work – the teams can do their design work effectively even though they are no longer co-located. But, we are cautioned that the systems integration issues are still very important and must be very closely managed by the Systems Engineers to ensure that in the end, an optimal system design is obtained.

The conventional wisdom within the company is that there must be co-location of system designers during the conceptual and preliminary design phases of an engine program, but as the key parameters that drive the system are defined (by the end of the preliminary design phase) the system designers can be dispersed to the Module Centers and can complete the detailed design there with the assistance of teams comprised of Design Engineers and supporting functions (e.g. structures, aero, drafting) with some level of system integration and coordination among the various component teams. The DSM analysis supports this view.

4.5 Summary

This chapter served to introduce the reader to the basic gas turbine aero-engine, common in today's commercial airline fleets. Engine components and functions were described, followed by a description of the early system design process, which is driven by requirements and constraints on design parameters related to each of the system components. These parameters were compiled and defined for the seven system components covered in this thesis. The Design Structure Matrix was then used to capture the dependencies between these parameters at a component level. We have built component level DSMs each with a block of highly coupled design parameters that lies on the diagonal of the matrix, indicating the relative complexity of the component design, in and of itself. Each component DSM shows that there are also interactions between components, mostly shown by how upstream or downstream component design parameters influence the design of the component; e.g. LPC and LPT interactions. The individual DSMs were then integrated into one large system level DSM which is used to identify the system level parameter interactions.

The DSMs have provided insight into the component and system design processes by diagramming their information flows. Although most engineers involved in the aero-engine design process would have had a sense that the parameters that drive the design are very much interdependent, few would have been able to explicitly state these inter-dependencies. The blocks in the System Level DSM clearly show why the design of the components and the system is complex, but also that the complexity can be managed at the boundaries of the individual components. This boundary management task is by no means trivial, given the fact that P&W will undertake the design activity at four geographically distributed Module Centers, each containing a number of component teams and sub-component teams (the CIPTs and IPTs respectively). The Systems Engineers will be responsible for ensuring that the components meet their specifications and that the engine system meets its specification for TSFC Thrust, reliability. This is a shared responsibility because the Component Teams are ultimately responsible for making sure that the component they deliver meets the requirements. The DSMs may help the System Engineers to understand where to look in order to "compile information" for making system level decisions, and by examining the feed-forward and feed-back loops of the System Level DSM, formulate approaches to root cause and corrective action planning in the event that a performance shortfall is discovered through analysis and/or system testing.

The most interesting finding in this chapter is that although the component design process is complex, the coupling between components is mainly through system level design parameters such as "Thrust" and "Total Specific Fuel Consumption", parameters that must be managed by the Systems Engineers (refer to the System Level DSM in Figure 4-2). We conclude that once target values for the system level parameters are defined and documented, the geographically distributed component teams will be able to work on their designs with relatively little interaction with the other component teams, except through the *significant* integrative efforts of the Systems Engineers. P&W must have a strong Systems Engineering Organization and Process, managed by the Systems Engineers, that ensures that the components can be reintegrated in a system optimizing manner at the completion of the component design process. They must send forth the important requirements, ensure that they are understood, and gain buy-in for them early in the process. They must then keep track of each Component Teams to ensure that they are able to deliver on the Component Requirements.

The next chapter will discuss Systems Engineering as practiced at P&W. The Systems Engineering Process that has been implemented is very high level task oriented. In Chapter 6 we will map the system design parameters discussed in this chapter to the Systems Engineering Process tasks described in the next chapter.

Chapter 5

Systems Engineering at P&W

> *Systems engineering is a branch of engineering which concentrates on the design and application of the whole as distinct from the parts....looking at the design problem in its entirety, taking account all the facets and all the variables and linking the social to the technological.*
>
> Simon Ramo
> Co-founder of TRW

This chapter will discuss Systems Engineering as defined and practiced at P&W. The Systems Engineering Groups were formally introduced at P&W early in 1997; the Systems Engineering Process was introduced early in 1998 with the intent of guiding the activities of the new organization. Systems Engineering processes are currently being defined not only in the aerospace industry, where they have been commonplace since the 1960s, but in many other industries as well, with a focus on improving the internal product development processes of the firm. This chapter will begin with a review of some of the Systems Engineering activities in the automotive industry. We will then move on to review the motivation for adoption of a formal Systems Engineering approach at P&W.

For the purpose of designing and developing a large complex system, it is common practice to decompose the system into sub-systems or components. Integrated Product Teams (IPTs), comprised of members with various functional expertise, design the system components. To assure that the top-level system works, these IPTs must work together during the design process. Systems Engineering is an approach common in the aerospace industry, but is not consistently defined or applied in industrial practice. Pioneered in the early days of the industry at firms like Hughes and Lockheed, Systems Engineering is a process in which the integrity of the product is ensured by the definition of systems level requirements that are driven by the customer and market. These requirements are then flowed down to lower and lower levels of the system hierarchy. Among other roles, System Engineers are responsible for deriving component level requirements from the top-level system requirements to ensure that the component designs are consistent with the overall system requirements. Another key role of the Systems Engineers is to resolve issues that arise across components. McCord and Eppinger describe the role of "Conflict Resolution Engineer and Liaison Roles"[29] who act as arbiters between development teams. As described by McCord and Eppinger, these people do not hold development task responsibility, but serve to resolve technical conflicts that arise between teams.

5.1 Systems Engineering In the Automotive Industry

In the Aerospace industry, Systems Engineering grew out of programs that could be characterized as "one-ofs", such as spacecraft design projects. The risks of system failure were great, and the consequences severe, measured in the loss of millions of dollars or potentially the loss of life, depending upon the program. The pressures on design teams to ensure that "things go right" were therefore very high, and Systems Engineering approaches to managing the development of these large complex aerospace systems were shown to be very effective.

Systems Engineering has recently become popular in many manufacturing industries, aerospace still among them, but also in others such as computer hardware and software development and automotive. The products of these industries are hardly characterized as "one-ofs", these are mass produced products. The interest in Systems Engineering is in its comprehensive and structured approach to the product development process, a process that take the firm from the gathering of customer needs through design, production, and retirement of the product.

Several automotive firms have adopted Systems Engineering approaches to product development. The following discussion reviews some of the experiences of three firms, General Motors, BMW, and Ford. This discussion is relevant because, as we will see, the motivation for Systems Engineering in the automotive world is very similar to the motivation at P&W for adopting a Systems Engineering approach to engine development.

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[29] McCord, K.R., Eppinger, S. D., "Managing the Integration Problem in Concurrent Engineering," MIT Working Paper 3594-93-MSA, August 1993.

5.1.1 Systems Engineering at General Motors[30]

General Motors (GM) defined a concurrent engineering organization in 1986 in an effort to streamline their product development process, to reduce development and end-product costs, and to speed their time to market with new product offerings. GM implemented Integrated Product Development and managers quickly understood that there was a lack of coordination of the Integrated Product Teams (IPTs) at the system level that resulted in interface problems between the IPTs. The IPTs were effective being part and sub-assembly focused, but the teams and the organization encountered difficulties as sub-assemblies and components were integrated into the top level vehicle system

To improve their concurrent engineering practice the Systems Engineering group was established in 1990. The Systems Engineering Process at GM made the System Engineer responsible for the following activities: a) requirements engineering, i.e. the gathering of customer requirements, generating top level system requirements, and flowing those requirements down to components, sub-components, etc.; b) conducting trade studies at various stages of system development; c) conducting periodic design reviews; d) WBS definition; e) Configuration management during the system life cycle; f) Creation and maintenance of the "Engineering Notebook" and "Program notebook" for lessons learned and to enhance the organizational learning process; h) Maintenance of a platform database; and i) risk management.

Mattis analyzed the effectiveness of implementing Systems Engineering at a General Motors, and in particular, examining who is selected as a Systems Engineer and what their responsibilities as such are. He notes that in order to implement Systems Engineering, the company had to "develop a specific structure within Product Engineering to support the process" reporting to the Chief Engineer.[31]

In summary, GM implemented a concurrent engineering process in order to improve product development process performance. Systems Engineering was added to augment the concurrent

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[30] Mattis, David P, "Systems Engineering Process at General Motors," MIT MS Thesis, Management of Technology Program, June 1992.

[31] Ibid., Mattis.

engineering organization and ensure that systems integration was properly in focus by coordinating the efforts of the various IPTs.

5.1.2 Systems Engineering at BMW

BMW is a second example of an automotive firm that has turned to Systems Engineering concepts to improve the product development process. Fricke et al[32] report that BMW had identified the need to model the product development process to provide a basis for improvement. Presumably BMW is looking for opportunities to streamline the development process in the same way that GM was in 1986, with a resultant reduction in development costs and time to market.

The ZOPH Model[33] is described as a comprehensive systems modeling approach that in many ways incorporates elements of systems engineering. ZOPH is derived from the German terms

- Zielsystem (goal system)
- Objektsystem (product system)
- Prozeβsystem (process system)
- Handlungssystem (agent system).

The goals of the ZOPH process are to enhance and encourage the flow of information in the product development process and between development teams in order to reduce development costs and cycle times. The ZOPH model is described as having the following characteristics[34]:

- **Transparency**: a roadmap, get people to understand what part they play;
- **Understanding and Learning**, support and communicate understanding of complex processes;
- **Coordination** of flows of information, money, material, etc;
- **Better planning and management** through transparency and coordination of activities;
- **Documentation and Reusability**, provide a starting point for the next project;
- **Prerequisites for Audits, model documents the process.**
- **What-if Analysis**
- **Basis for Process Assessment and Improvement**
- **Shorter Development Cycles**

These goals are similar to many business process re-engineering and systems engineering process goals in other industries. Fricke and his co-authors recognize the integrated nature of the design process and the different types of task/parameter interrelations (sequential, parallel, coupled).

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[32] Ibid., Fricke.
[33] Ibid., Fricke.
[34] Ibid., Fricke.

5.1.3 Systems Engineering at Ford Motor Company

Ford is the final automotive company to be considered. The Ford 2000 initiative has been underway for several years, with goals similar to those described above for the other automotive manufacturers considered, namely an optimized product development process that results in better products, faster, and cheaper. Ford 2000 contains two "sub-initiatives" aimed at improving the processes within the firm. The first is called "Ford Production System" or FPS, which is directed at the manufacturing side of the firm.

The second piece is called the "Ford Product Development System" or FPDS, which is a Systems Engineering Process that guides the development of all vehicles at Ford. Development of FPDS was begun in 1995. It is a program whose development required the efforts of about 200 engineers working for a year (200 man-years), and the team included people from Manufacturing, Powertrain, Purchasing, Corporate, Design, and all functional groups. FPDS is a classical systems engineering top-down process in which customer requirements are used to develop high level system requirements that can then be flowed down to sub-systems, sub-sub-systems, etc. The requirements flow-down process continues down to the individual part level. FPDS consists of a Work Breakdown Structure with associated Gannt Charts. The WBS hierarchy goes 6-7 levels deep, and at each level there is a definition of systems engineering type tasks that must be completed depending on the phase of the vehicle design. Design phases include: Define Requirements, Detailed Design, and Verification. Several student interns at Ford in recent years have reported that FPDS has been very difficult to implement within the product development organization. FPDS is characterized as a "top-down" development process, which is what one would expect in a systems engineering process. The concept of a top-down process is great, but people are bottom-up thinkers, and it is very difficult, and maybe even not worthwhile, to try to get them to think top-down.

In the past, Systems Engineering may not have been formally recognized at Ford, but the idea of system level issues is not anything new. Ford has what are called "Attribute Teams" that deal with vehicle system attributes, for example Noise Vibration and Harshness.

In summary, Ford is turning to Systems Engineering for the same reasons other automotive firms have: to add structure to a product development process, to provide a mechanism to analyze an improve upon the current processes. In the end, the goal is reduced product development cycle times and cost with high quality output.

5.1.4 Applicability of Systems Engineering to Automobiles

One of the interesting differences in the application of System Engineering principles to the automotive design process is that the customer requirements are necessarily "fuzzy". Requirements come on the flavors of "Nice Appearance", and "Fun to Drive", and "Tight Handling", and "Great Sound". These characteristics are very different from the sharp quantifiable requirements that are typical of an aerospace system like a satellite or a jet engine. In the engine world, the requirements, even at the very top level are quantifiable, at even at a very high level requirements on Cost, Weight, Performance are identifiable.

5.2 Systems Engineering at P&W

In section 5.1, we reviewed several systems engineering initiative in the automotive industry. As was pointed out earlier, systems engineering has been popular and successful in aerospace since the 1960s, especially because aerospace firms often were developing "one-of" systems that had to perform flawlessly the first time. The 1980s and 1990s has brought a focus on "process" at manufacturing firms, with business process re-engineering popular in a variety of industries. We saw in the preceding sections that GM, BMW, and Ford were all interested in improving their product development processes in order to enjoy lower cost development programs that brought new products to market at a quicker pace. Each turned to Systems Engineering to help improve.

P&W had an experience similar to GM's as described by Mattis, namely the problem of systems integration in the IPD environment. As was described in Chapter 2, in the early 1990's P&W moved to an Integrated Product Development Process (now referred to Integrated Program Deployment Process internally at P&W). Four years after IPD was implemented, P&W defined the formal Systems Engineering role to augment the product development organization, for reasons similar to GM's. The following section discusses the Systems Engineering groups now in place at P&W and also introduces the P&W Systems Engineering Process.

A formal Systems Engineering function was added to the overall product development process to address several documented concerns of P&W management. First, since the Component Center structure was put in place in late-1993, there were concerns about the impact on the effectiveness and cohesiveness of the overall engineering organization. For example, there was a concern that the Component Centers would create new functional chimneys, which was a move counter to where P&W had been trying to move over the preceding 2-3 years. Second, the split of engineering between the technical and program management roles (as described in Chapter 2, section 2.3.3.1) was seen as a net detriment to effective program planning and technical execution. It had become very difficult to move people between the component centers and the engine programs and vice versa. Deployment of company "best practice" between engine programs was inhibited because the common tie (functionality) was no longer intact.

The introduction of the Systems Engineering Groups was envisioned to provide a mechanism for discipline (functional) responsibility to be restored by reuniting all of engineering and providing a means to manage distributed engineering. The first three Systems Engineering groups are very heavily aligned with the engineering organization (Propulsion Systems Analysis, Product Development and Validation, and System Design and Component Integration). The fourth group, Manufacturing Systems Engineering and Integration was initially not included in the overall systems engineering strategy, but was added shortly after the first three Systems Engineering groups were announced.

5.2.1 P&W Systems Engineering Groups

The UTC definition of systems engineering was used as a starting point for defining Systems Engineering at P&W:

> Systems Engineering is the process which rigorously translates customer needs into a structured set of specific requirements, synthesizes a system architecture that satisfies those requirements, allocates them in a physical system, meeting cost, schedule, and performance objectives throughout the life cycle.

This definition was developed by members of a systems engineering working group that had members from each of the United Technologies business units.[35] Members included executives from all of the UTC Business Units (Carrier, Otis, UT Automotive, Flight Systems, and P&W). This group recognized systems engineering as one process key to the success of a product development process, a piece that was closely integrated with Program management and integrated product development processes. In the Spring of 1997, four systems engineering groups were created at P&W to augment the product development organization as it existed at that time. The overarching roles and responsibilities of the Systems Engineers are to insure that a plan to achieve all engine program objectives (weight, cost, performance, customer requirements, etc.) is in place and is whole at all times. All four Systems Engineering Groups are responsible for CIPT task initiation and approval, conducting Design reviews, and engine configuration management. The four Systems Engineering Groups and their specific roles and responsibilities are defined as follows:

Propulsion Systems Analysis and Integration (PSAI)

The Propulsion Systems Analysis and Integration engineers are similar to the "System Analyst" role defined by Sheard[36] "system analyst/performance modeler/keeper of technical budgets/system modeler and simulator/etc. Confirm that the designed system will meet requirements". At P&W the PSAI engineers are responsible for interpretation of customer requirements and translation into design tables and performance and operability specifications, analyses, and simulations that aid in the design of the system and its components. At any stage of the system life cycle, the PSAI engineers identify performance and operability shortfalls and define recovery plans and solutions to eliminate these shortfalls and therefore play an integral role in the development and certification of the engine system.

After the engine system is Certified (by the FAA/JAA/CAA for commercial engines), the PSAI engineers analyze and track flight test data, thrust ratings and power settings. The are also owners of the "engine audit" process in which overall performance of the engine is assess by evaluation of each component.

Systems Design and Component Integration (SDCI)

The SDCI Engineers are recognized by Sheard as the "System Designer Role: System designer/owner of the system product/chief engineer/system architect/developer of design architecture/etc.". The SDCI engineers are responsible for interpreting customer requirements and

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[35] The business units are Pratt&Whitney, Sikorsky Aircraft, Hamilton Standard, Otis Elevator, Carrier, and UT Automotive.

converting into a System Requirements Document that is then flowed down into a Component Requirements Document. SDCI engineers are also responsible for the overall propulsion system structural integrity, which includes the following:

- Secondary flow system/thrust balance;
- Statistical support (lifing, failure rates, etc.);
- Reliability and Fault Tree analysis;
- Engine/Airframe mechanical integration;
- System Level Structural Tasks (e.g., Low Cycle Fatigue lives, Rotor Dynamics, Whole Engine Model/Blade Out Loads);
- Technical Support for engine certification/qualification and certification reporting;
- Engine model task tracking;
- Engine weight tracking and management;
- Cost reduction management and tracking;
- Assembly level drafting;
- Risk Management Plans.

The System Design and Component Integration engineers are responsible for the formal Design Review Process at P&W. In addition, they manage the configuration (BOM) of the system through the Configuration Control Board. During the conceptual and preliminary design phases of an engine program, they are tasked with managing the development and documentation of the System Requirements Document and the Component Requirements Document that drives the design of the entire propulsion system.

The Systems Design group is also owner of the design tools employed during all phases of the system design. As such, they are tasked with maintaining existing tools and also development the state-of-the-art analytical and design tools that will enable the design of advanced propulsion systems in the future. These tools include the development of the latest Computational Fluid Dynamics modeling systems for aerodynamics design, and advanced coupled aerodynamic/thermal/structural design tools useful for predicting temperatures, clearances, and lives of hardware. In addition to owning the design tools, the System Design engineers also own the design process.

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[36] Sheard, S. A., "Twelve Systems Engineering Roles," Software Productivity Consortium, 2214 Rock Hill Rd, Herndon, VA 22070.

Product Development and Validation (PDV)

The PDV Engineers are recognized by Sheard as the "System Validation and Verification Role: test engineer/test planner/owner of the system test program/etc.". PDV engineers interpret customer requirements and create the development and certification test plans. PDV engineers manage the development and certification hardware and they direct the development and certification engine testing including development engine building, development engine tear-down and inspection.

Manufacturing Systems Engineering and Integration (MSE)

The Manufacturing Systems Engineering role is not recognized by Sheard. The prime responsibility of the Manufacturing Systems Engineers (MSE) is to insure that the time to market, cost to market, and quality of the engine or propulsion systems (recurring cost, weight, etc.) meet the actual or implied assumptions in the program venture analysis and the program contract. In order to execute this prime responsibility, the Manufacturing Systems Engineers have the following authorities and responsibilities: they must insure that all program assumptions concerning time to market, cost to market, and quality of the propulsion system are consistent with current best manufacturing practices. They will direct manufacturing engineers assigned to the programs to insure that all parts are designed and processed to internal P&W standards including Charter Parts Norms and Value Engineering, existing and proven manufacturing processes, low cost tooling and fixturing, and simplified work instructions. The MSE will be responsible to insure that parts are processed and quickly learned out by employing tools such as Quality Control Process Charts, Poke Yoke, and process certification. The MSEs shall also have responsibility for conducting design reviews, managing the introduction of hardware into the development programs and initial production, and coordination of capital and tooling requirements, both initial and rate.

Role Shared by All Systems Engineering Groups

All the Systems Engineers are members of the Program Integrated Product Management Team (IPMT) that manages (funds and provides manpower) the daily activities of the engine program. From the start, Systems Engineering at P&W was envisioned to be an integral part of the overall product development process. Figure 5-1 shows how systems engineering fits into the overall product development structure within P&W.

The Systems Engineers are also expected to be an integral part of the program management team, the Integrated Product Management Team, the team that owns the decision making process regarding resource allocation, budget priorities, the general management of an engine program. Each engine program is assigned a Systems Engineering Program Manager from each of the four Systems Engineering Groups.

Sheard[37]: also outlined several other roles that are shared by the Systems Engineering Groups at P&W:

1. Coordinator Role: Coordinator of the disciplines/head of the integrated product teams/system issue resolver.
2. Technical Manager Role: Planner, scheduler, tracker of technical tasks, owner of risk management plan. Also share this role with the Program office.
3. Process Engineer Role: The Process Engineer is the owner of the systems engineering process. They document, follow, own, and improve the firm's systems engineering processes by defining and capturing systems engineering metrics.
4. Requirements Owner Role: owner/manager/allocater/maintainer/spec writer/developer of the functional architecture. Share this role with Advanced Engine Programs group. The first step is the translation of customer needs into well written and specific requirements to which the system elements can be designed.

The most important systems engineering role defined by Sheard but not explicitly covered by the Systems Engineering Groups is the "Glue Role"[38]: The engineer in the "Glue Role" is the boundary manager and owner of the internal interfaces who seeks to find all the issues that would fall

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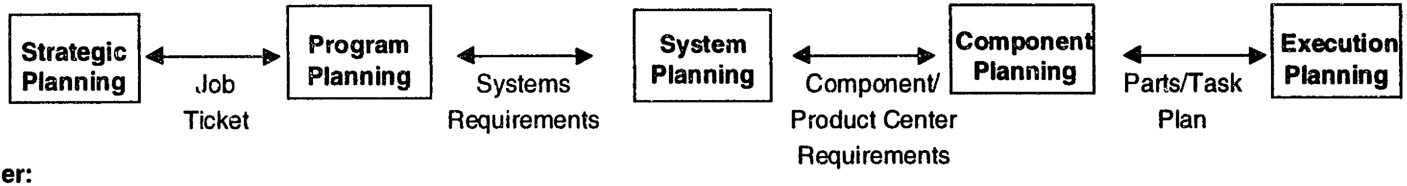
[37] Ibid. Sheard.

[38] Ibid. Sheard.

Figure 5-1

P&W INTEGRATED PROGRAM DEPLOYMENT PROCESS



	Strategic Planning	Program Planning	System Planning	Component Planning	Execution Planning
Owner:	PW Exec Council	IPMT	Chief System Engineers	Component, Product, and Service Centers, plus Materials	IPT & Business Units
Roles & Responsibilities	1. PW Mission 2. Success Tree • Customer • Employee • Business • Process ⇧ • LME plan • LCE plan • AMS plan • R&S plan 3. PW Policy	1. Product Plan • Customer • Define • Produce • Service • Business 2. Master Schedule 3. Resource Reqts 4. Metrics	1. Systems Plans • Performance • Design • Validation • Sourcing • Processing • Cost • Service 2. Level I Schedule 3. Quality Plan 4. Delivery	1. Component Plans • Technology • Process(s) • Costs • Supply 2. Level II Schedule 3. Resource Deployment 4. Conformity Validation	1. Parts/Tasks • Delivery • Cost • Quality 2. Level III Schedule

through the cracks, identifies risks and serves as the technical conscience of the program. Glue Systems Engineers need wide experience and meaningful domain knowledge. The Glue Role is functionally different from that of the System Design and Component Integration engineers because this engineer should be positioned as the first line of defense against design integration escapes: they are involved in the work of the component teams on a daily basis. They have an intimate understanding of how the component design is evolving, but remain focused on how this evolution impacts the other components, and are therefore ready at any time to contact counterparts on the other component teams and at other Module Centers to insure design coordination and synchronization.

5.2.2 P&W Systems Engineering Process

The process of systems engineering is central, and indeed many people define systems engineering as being the process.[39]

By the summer of 1997, four months after the Systems Engineering Groups were introduced, it had become clear that a P&W Systems Engineering Process was necessary to provide a roadmap for the newly minted Systems Engineers to follow in order to successfully accomplish their day-to-day tasks. The Systems Engineering Process Team was formed in July of 1997. The team objective was to

> Establish a world-class engineering process that formalizes systems engineering at P&W. The process and the means by which it is communicated will enable systems engineers to successfully understand and accomplish their tasks. This process will share the best practices from the various organizations, work to the industry standards and will be measurable and tracked on a regular basis.[40]

As a starting point, the team used the UTC Systems Engineering process, which is modeled very closely after the Electronic Industries Association EIA 632, Version 0.8 systems engineering process. The UTC high level process is shown in Figure 5-2.

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[39] Murman, E. M., "Thoughts on System Engineering," unpublished work, Department of Aeronautics and Astronautics, MIT, September 1997.

[40] Internal P&W Systems Engineering documentation.

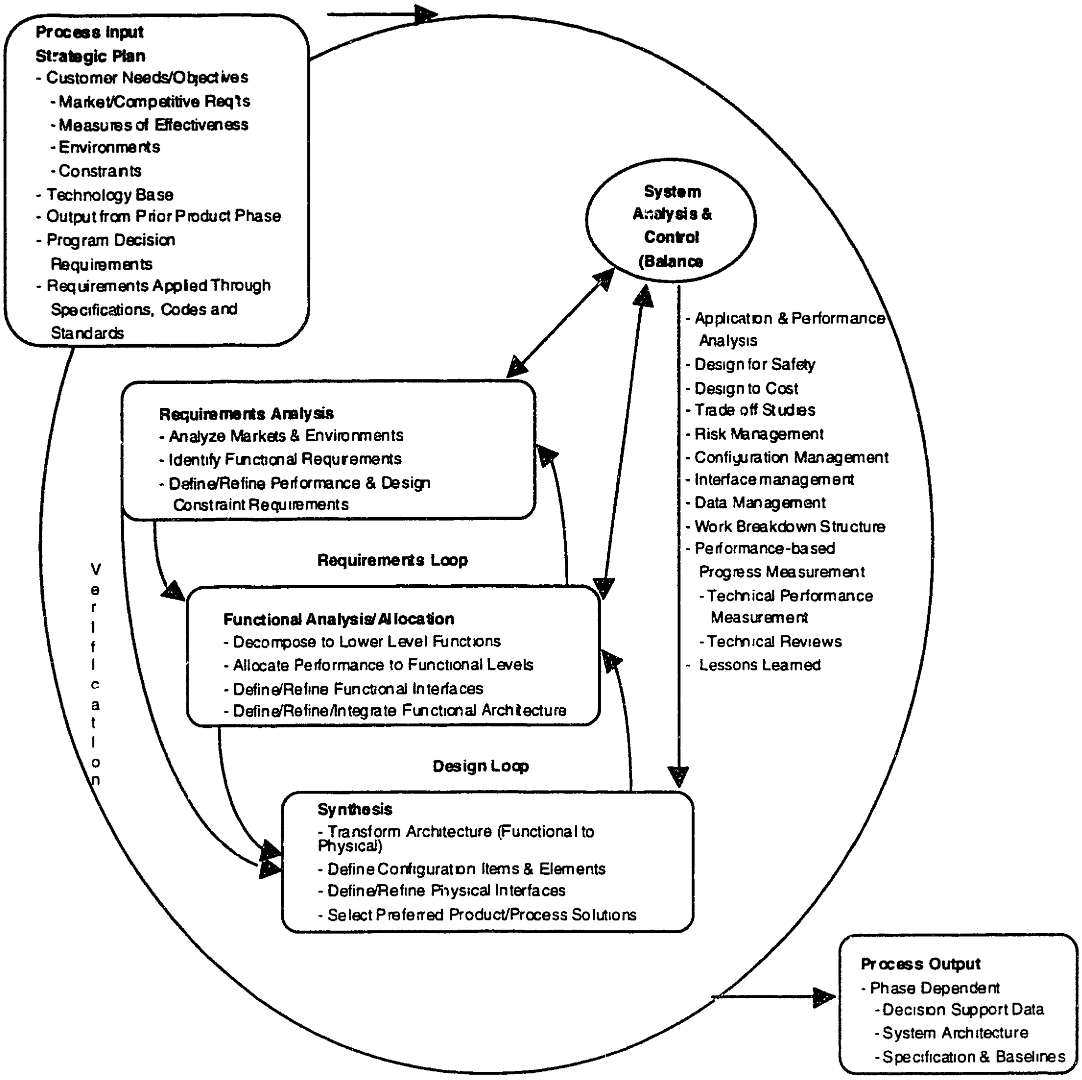

Figure 5-2
UTC Systems Engineering Process Framework

Figures 5-3 through 5-10 in Appendix C represent the P&W Systems Engineering Process as defined by the Systems Engineering Process Team. The figures show that the engine development process can be partitioned into distinct phases:

1. Input phase
2. Concept phase
3. Detail design/make phase
4. Verification/validation phase
5. Flight test phase
6. Product Support/Customer feedback phase
7. enablers

The flowcharts presented in Appendix C are the first pass at a process and are intended to represent a very high level view of the tasks that the Systems Engineers are responsible for in the system design process. It is implied that there is a lot of "how" information that resides underneath each of the "what" boxes displayed in the process. The process resides on the internal P&W Intranet, and each box in the process is actually a "hot-button" that the user can click on to get further information about each specific task. Several examples of tasks are provided below to give the reader a feel for the types of tasks in the process. Additional examples from the web site are included in Appendix D.

Example 1

Task Name:
Define/Document System Requirements
Description:
Systems requirements are defined by using the customer's specification or other applicable document in conjunction with P&W's strategic product and technology plans. They also include applicable government/regulatory requirements combined into the "Propulsion System/Component Requirements" document. The document is signed and issued at program launch and can be modified by an appropriate process thereafter. The document is divided into four sections: Systems, components, major parts, and resources.
Process Deliverables:
The "Propulsion System/Components Requirements" document

Example 2

Task Name:
Verify System Requirements and Specifications are Met
Description:
Using the Propulsion System and Component Requirements document as the baseline, employ the systems processes that ensure requirements are met. A requirements tracking/progress process that is commonly deployed is not yet available. The process, however, uses Program Management to plan and direct activities, the IPD process designs, makes, validates, certifies and services the product and the Systems Engineers tie the processes together. They use the Configuration Control Board, The Product Data Manager and the Design Review to actively monitor progress and drive the product to meet requirements.

Process Deliverables:
By anticipating or identifying items that have the potential to or will not meet requirements, direct corrective actions to the appropriate group/department.

5.3 *Analysis of the P&W Systems Engineering Process*

One of the original goals at the outset for this thesis was to complete a Design Structure Matrix analysis of the P&W Systems Engineering Process. The intent was to understand the information dependencies between tasks, to cluster tasks into higher level "meta-tasks" or "sub-processes", to identify leverage points in the process where rework is generated, etc.

The P&W Systems Engineers were questioned about their understanding of the information dependencies and inter-relationships between tasks. When asked to characterize the inter-relationships between tasks in the Process, the Systems Engineers indicated that there was a very high level of coupling between all the tasks through information dependencies. In an alternative approach to characterizing the task interdependencies, data were gathered from the Systems Engineering web-site regarding information sources and deliverables for each task. From this information we could infer the information interdependencies. A story different from the engineer interviews emerges using this data collected from the web: there is little coupling amongst the tasks in the Systems Engineering Process, based on the web-site documentation. Some possible explanations for this result are:

1) P&W is similar to Ford[41]: at a part level, internal documentation related to the design of specific pieces of hardware is fairly complete. One does not have to rely heavily on the knowledge of local area experts to complete the job because the job is well documented. As one moves in complexity to assemblies and from there up to components/systems, the local area expert was found to be critical to the understanding of the system design. That is, the documentation captured only a fraction of the information required to complete the design tasks. P&W may have the analogous situation, in which the information interdependencies documented on web-site are lean compared to what the experts expect for inter-task dependencies.
2) Black[42] found in his research that the engineers tend to over complicate the information dependencies, in this instance, requesting too much information, much of it irrelevant to the design. This might explain the tendency for the systems engineers to report such high coupling of all the tasks in our process – they have a gut feeling that there is a coupling, but to explicitly state the information dependency might be more difficult.
3) The documentation for the Systems Engineering Process is still in a nascent state and as time goes on and the process is further developed, documentation sources and deliverables will be added for each task and the information coupling will become greater. We observed during the research and data collection that the tasks in the Process are not all that well understood by the

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[41] Dong, Qi, "Representing Information Flow and Knowledge Management in Product Design Using the Design Structure Matrix," MIT MS Thesis, February 1999.

[42] Black, Thomas A., "A System Design Approach to Automotive Brake Design", MIT MS Thesis, 1990, p26.

Systems Engineers themselves. A common question was "What does this task mean?" There are several possible explanations for this including a) the newness of the process; b) variation in terminology. One thing the process can provide is standardization of terminology across the enterprise; c) the task is outside of the person's duties, so he/she does not recognize it; d) The task is part of the person's duties, but he/she does not recognize responsibility or ownership.

5.4 Summary

In this chapter we examined systems engineering in general. We saw that systems engineering was heavily in use in the aerospace industry since the 1960s, especially for "one-of" systems. The implementation of a systems engineering process has gained favor in other manufacturing industries in recent years because it provides a structured approach to product development that can help a firm achieve improvement in development costs, time to market, and product quality. We reviewed the systems engineering experiences at three automotive firms, and then examined how systems engineering was being implemented at P&W— with motivations similar those in the automotive industry.

We considered the Systems Engineering Group structure in the context of organizational change at P&W. We examined the roles of the Systems Engineers, comparing and contrasting them with the generic systems engineering roles defined by Sheard. We saw that a very important systems engineering role, the "Glue Role", is missing from the systems engineering implementation at P&W, a role we believe is critical to the success of the Module Centers in the future.

We closed the chapter with a review of the P&W Systems Engineering Process. In the next chapter, we will see how the System Engineering Process as defined here can be linked to the actual process of designing the system. What are the implications of this mapping in the context of Module Centers and how does systems engineering allow P&W to actually practice product development with geographically distributed design engineering and manufacturing resources.

Chapter 6

Use of Systems Engineering To Facilitate Distributed Product Development

This chapter will define how the Systems Engineering Organization and Process are linked to the system design through the design parameters documented in Chapter 4. We will specifically examine the role of the Systems Engineers in the Module Centers. As was mentioned in Chapter 5, the P&W Systems Engineering Process is very high level task oriented and can serve as a roadmap for the Systems Engineers, guiding them in some of the basic day-to-day functions for which they are responsible. The ultimate goal is the delivery of a propulsion system that performs to the customer requirements. Since the system design is captured in the definition of the design parameters (rather that Process tasks), the Systems Engineers must remain focused on the parameters at all times.

6.1 Systems Engineering and System Design

Recall from previous chapters that P&W is moving to an increasingly more distributed engineering and manufacturing organization in the form of Module Centers. Manufacturing facilities have been geographically distributed for many years at P&W, with locations in East Hartford, Middletown, and North Haven Connecticut, North Berwick Maine, and Columbus Georgia. The Engineering organization has been centrally located, with commercial engineering in East Hartford and military engineering in West Palm Beach Florida. Following the move to Module Centers, design engineering will be as geographically distributed as the manufacturing organization has been, with each manufacturing facility gaining its own complete design engineering capabilities.

The goal of this further integration of design engineering and manufacturing is to reduce development costs and ultimately product costs. But the disintegration of the design engineering organization carries with it certain risks, not least among them the loss of systems integration activities that had occurred in the past, in many instances simply by virtue of co-location of component design teams in East Hartford (commercial engines) or West Palm Beach (military engines). In the new Module Center structure, the component design teams will not be co-located with one another. The design of components that comprise Compression Systems (Fan/Low Pressure Compressor/High Pressure Compressor) will be carried out in Middletown, while the design and manufacture of Turbine Systems (High Pressure Turbine/Low Pressure Turbine) will take place in North Haven. Although the communications between components that reside within the same Module Center may be maintained, the communications and system integration between components that are at a distance will not be as straight forward. (note that for the sake of simplicity we will not discuss the Combustor/Augmentors/Nozzles Module Center or the Externals Module Center).

A reduction in systems integration activity is anticipated because informal communications channels between component teams will be lost when the teams are no longer co-located. Informal cross-component communication is an important part of the development process. In the past, close proximity via engine program co-location facilitated this activity. But management must not rely too heavily on these informal processes because:

- the probability that the engineers will always remember all of the important interactions between component teams is low;
- informal processes are unstructured by nature and do not handle unforeseen inter-component conflicts well;
- inter-component communications do not occur often when component teams are geographically distributed, as they will be in the Module Centers.

The Systems Engineers will play a significant role in ensuring that this distributed team strategy of Module Centers is successful in practice at P&W. One of the tools available to the Systems Engineers to ensure this success is the wealth of system level knowledge shared among the Systems Engineers. Another tool is the Systems Engineering Process itself. In order for the Process to help facilitate product development in a distributed engineering and manufacturing environment, we must understand how the process is related to the actual design of the system; i.e., what are the things that the Systems Engineers are responsible for that will enable the individual design teams to design components in the Module Centers with the confidence that the systems integration issues are adequately addressed, such that the overall propulsion system performs as expected once the components are integrated into the top level system.

We propose to demonstrate the integrative role of the Systems Engineers by reviewing two examples of how the design parameters are related to the Systems Engineering Process. We will draw on the Design Structure Matrices (DSM) of Chapter 4 and the Systems Engineering Process presented in Chapter 5.

6.2 Example 1 – Component Design at a Module Center

Recall from Chapter 4 the component level DSMs. It was shown that each component design was dependent upon a) a set of system level parameters that were defined prior to the component detailed design iterations; b) a second set of parameters that clearly drove the design of the particular component; and c) a third set of parameters that not only influenced the component under investigation, but also influenced other component designs as well.

It was also shown that when we integrate all of the individual DSMs into a system level DSM we observe a large set of system level parameters that influence the design of all the components in some way, causing coupling of the component designs. But Figure 4-2 in Chapter 4 also shows that if these system level parameters are sufficiently defined, they can be taken as inputs into the component design processes which de-couples the component designs allowing them to proceed in "quasi-isolation". We use the term "quasi" because the coupling is not eliminated and must be managed by the Systems Engineers as the design progresses.

This implies that the component teams need some formal documentation of these initial parameter target values. These values are in fact documented in the System Requirements Document and the Component Requirements Document. Both of these documents are the responsibility of the Systems Engineers, in particular the System Design and Component Integration engineers. In this example, we can tie all of the system level parameters (Aircraft/Engine Range through Maximum Air Flow in Figure 4-2) to the Systems Engineering Process task entitled "Define/Document System & Component Requirements" which occurs in the Conceptual Design Phase of the design process, and also “Complete Requirements Documents” which occurs shortly after “Product Review 1”.

Figure 6-1 is a simplified view of the System Level DSM in Figure 4-2. The arrow on the left-hand side of the figure in Figure 6-1 indicates a flow of information from the system level design parameters to the components. As the component design progresses, there may be changes to the initial system level design parameter target values, changes initiated by feedback from the component designs (indicated by the arrow in the upper right corner of the figure). The regions across the top of the DSM and along the left-hand column are the regions of parameter interaction that the Systems Engineers must manage

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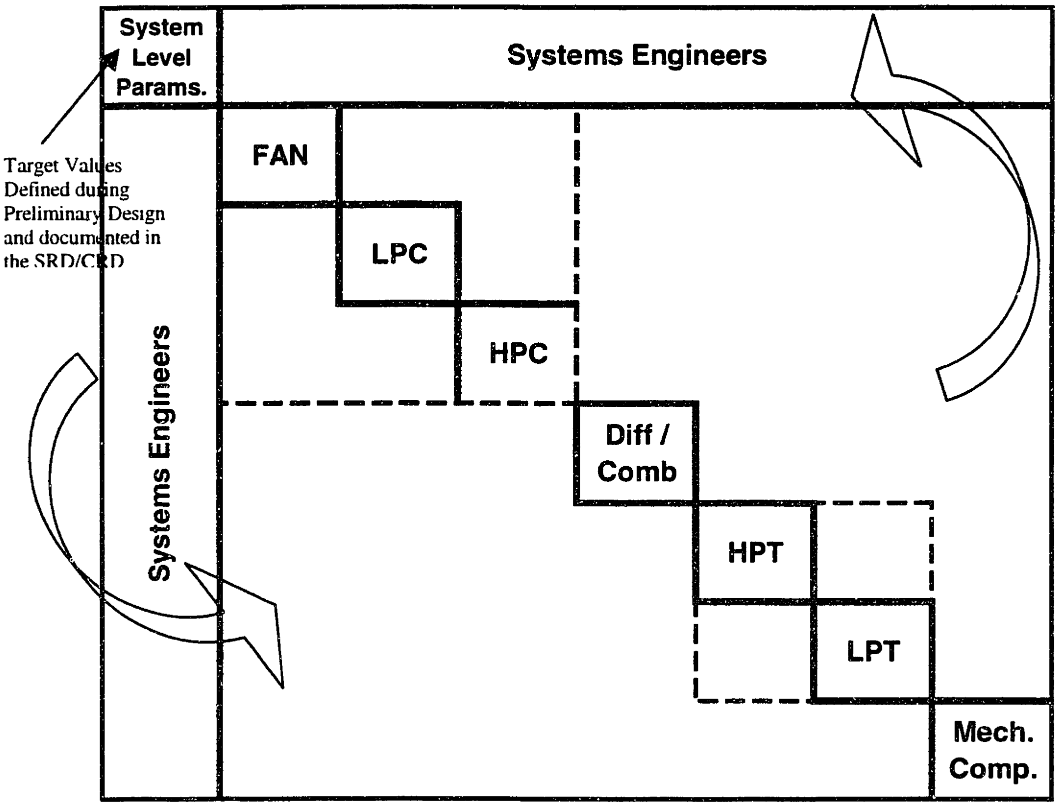

Figure 6-1
System Level Design Structure Matrix
The Systems Engineers manage the System Level Parameters as the detailed design progresses.

6.3 Example 2 – Inter-Component Design Issues in the Module Center

As a second example, consider the design of the High Pressure Compressor and the High Pressure Turbine. In the old structure, both the HPC and HPT designs would be completed in East Hartford for Commercial engines. In the new Module Centers, the HPC will be designed and built in Middletown, CT, while the HPT will be designed and built in North Haven, CT, about 40 miles away. The DSM in Figure 4-2 shows that there are inter-component communications between the two components through design variables. For example, Parameter "HPC Bleeds (Configuration & Flows)" influences the "Durability/Coating Selection", "HPT Airfoil Design" and "HPT Disk Design".

"HPC Bleeds" refers to the amount of the High Pressure Compressor flow that can be extracted and fed to the High Pressure Turbine to cool the hardware operating in the gas-path. The amount of cooling air supplied is a function of the HPC efficiency, among other parameters. It would not be unusual for a target value of HPC efficiency to be missed during the development process. In such an instance, one possible reaction is for the HPC design team to provide less cooling flow (i.e. less HPC Bleed air) to the HPT. This would in turn cause the HPT team to reconsider their designs, since less cooling are means higher metal temperatures, lower lives, etc. and they may to be able to accept the reduced cooling flow. This type of interaction, explicitly displayed in the DSM, is not uncommon during a design, and the design teams often know how to cope with such eventualities.

We suggest that the management of such inter-component parameter interactions be handled by the Glue Systems Engineers introduced in the preceding chapters. The Glue Role engineer is a systems integrator and owner of the internal interfaces of the system. In this role, the Glue Role engineer seeks to find all the issues that would fall through the cracks, identify risks and serve as the technical conscience of the program. He/she serves as a proactive trouble shooter, looking for problems and arranging to prevent them from occurring. The shaded region of Figure 6-2 shows the regions of interactions managed by the Glue Role engineers, with input from the component teams. The dashed boxes in Figure 6-2 indicate the boundaries of the Module Centers. Design integration within a Module Center is presumably easier than across Module Centers due to the co-location of the teams, and we expect the Glue Role engineers to work closely with the design engineers to address system level issues. The shaded regions indicate interactions between parameters that cross Module Center as well as component boundaries and are expected to be more challenging to manage.

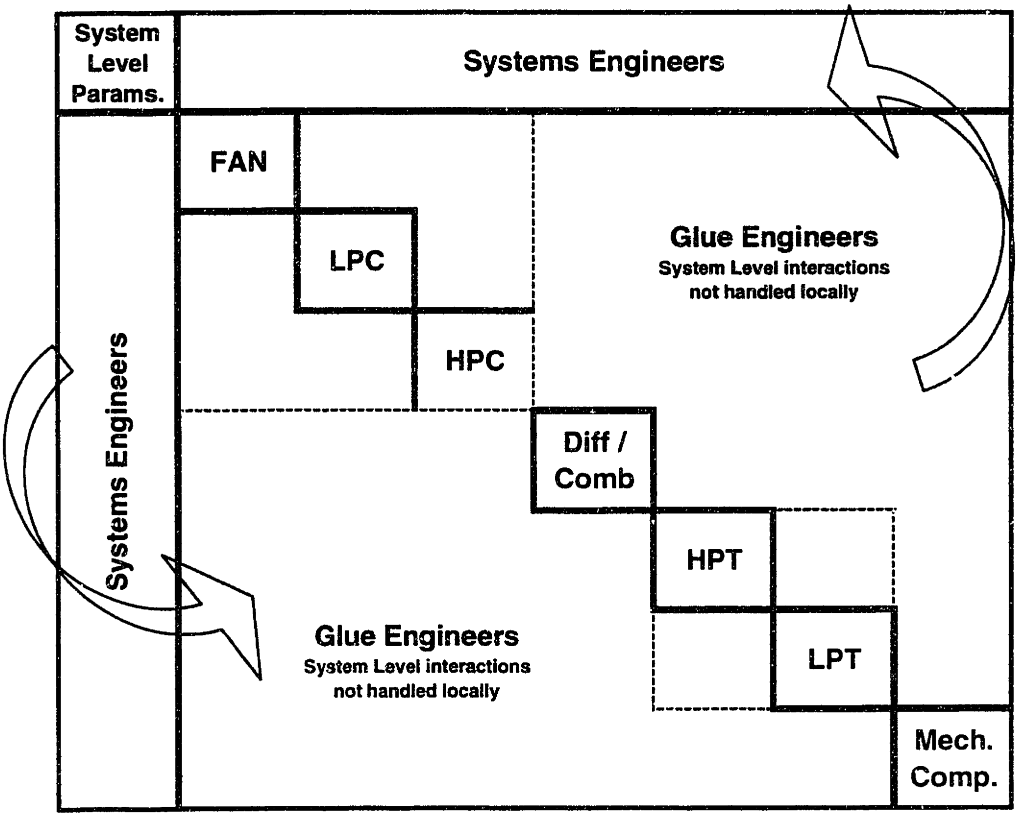

Figure 6-2
System Level Design Structure Matrix
The "Glue" Engineers are responsible for managing the parameter interactions in the shaded region.

6.4 Summary

This chapter built upon the findings of Chapters 4 and 5, integrating the system design DSMs with the Systems Engineering Process. We show that the process covers some of the fundamental responsibilities of the Systems Engineers. The most interesting lesson is in regards to the distributed engineering and function of the Glue Role engineer in managing cross-Module Center as well as cross-component interactions.

The Process does not contain tasks that enforce the continuous Systems Engineering activity of component integration work at the Module Centers. This may be due to the fact that in the current structure (i.e. just prior to full move to the Module Center Structure) the Component Centers jointly own this responsibility with the Systems Engineers. This does not adequately explain why the task is not found in the Systems Engineering Process, since there are other tasks that are jointly owned by the Systems Engineering Groups and the Component Centers. Regardless of the cause, the lack of specific systems integration tasks throughout the design process could, at a minimum cause confusion about who is responsible for the systems integration work, and at worst leave open the possibility that it is not adequately handled by anyone in the new Module Center structure.

Note that the Systems Engineering Process was defined prior to the announcement that the design engineering and manufacturing organizations would be merged into Module Centers, so the Systems Engineering Process team may not have anticipated the need for the Glue Role when the process was being defined. It is instructive to use the analysis of Chapter 4 and an understanding of how the engine design proceeds to suggest that the "Glue Role" be one that P&W consider for improving the Systems Engineering Organization. Along with the "Glue Role" there should be specific "Glue" tasks that are added to the Systems Engineering Process. These would be continuous tasks that are performed throughout the design process. This implies that the Systems Engineering organization is going to need human resources and budget to fund the Systems Engineering "Glue Role" at the Module Centers.

Chapter 7

Lessons Learned and Suggestions for Future Work

In the preceding chapters we have reviewed the evolution of the product development organization at Pratt & Whitney Aircraft. We analyzed the system level design process by evaluating the coupling between the parameters that define the design of the engine components using the Design Structure Matrix method that was introduced in Chapter 3. We also showed that although there is coupling between the individual engine components, this coupling is predominantly through system level design parameters, and we suggest that when these system level parameters are properly defined and managed the component design can be de-coupled and completed at geographically distributed locations, rather than requiring a centralized engineering organization as in the past. This result supports P&W's move to the Module Center Structure.

7.1 Research Findings

The following discussion summarizes three distinct lessons learned over the course of this thesis work. The first set is derived from the Design Structure Matrix analysis of the design parameter interactions. The second set of findings is based on the review of P&W's implementation of Systems Engineering and our mapping of the design process to the Systems Engineering Process. The third set is of general lessons based on the research approach. These lessons lead us to several recommendations regarding changes to the Systems Engineering Group structure and the Systems Engineering Process which we make in section 7.2.

7.1.1 Lessons Learned Based on the DSM Analysis

The first lesson relates to the explicit documentation of the parameter inter-relations that drive the engine design. It will not surprise the experienced aero-engine designer that the component designs are coupled. On the other hand, while a design expert may be able to specify the parameter inter-relationships in his/her area of expertise, it is unlikely that the expert will be able to quickly explain all the inter-relations. The component DSMs and System DSM presented in Chapter 4 are useful because they display these inter-relations in an easy to read form, and provide insight into the information flows via feed forward and feedback loops. The DSMs help the system designer understand the difference between the "core" parameters that drive the component design versus system parameters associated with links to other components.

In much of the literature, the DSM has been used to study the interactions of design parameters or design tasks for a piece of a system, an automobile engine throttle-body for example. This thesis uses the DSM to construct a system level model. By combining the seven component DSMs we were able to create a system level matrix which showed how the component designs are coupled through the information feed-forward/feed-back loops of the system level parameters, but can be uncoupled by defining a set of system level parameters. While the component design teams can not design their component in complete isolation from the other teams, with the proper system level parameter inputs, the teams can work in semi-isolation, with component boundary management provided by the Systems Engineers. The implication is that the Module Center concept that P&W will implement can work and that the trade of system integration through co-location of the IPTs for Design Engineering/Manufacturing integration by co-locating engineering design at the manufacturing centers, is a good one. The key to success will be the management of the system level parameter interactions.

7.1.2 Lesson Based on the Analysis of the Systems Engineering Process

As mentioned in the preceding section, the design of engine components by geographically distributed teams is possible, but the boundary management role of the Systems Engineers is critical for the flawless integration of the components into the top level propulsion system. Based on our review of the Systems Engineering Process, there is a need to add more explicit design integration tasks that are continuous, daily activities, rather than discrete events.

7.1.3 General Lessons

It is appropriate to comment on the approach taken to analyze the engine design process, the Design Structure Matrix (DSM). The DSM has found rather widespread success in recent years in a variety of industries including automotive and aerospace. The typical applications have been for team-based modeling of a process for organizational design, task based modeling as we had proposed for an evaluation of the Systems Engineering Process, and parameter based modeling, as was our application in Chapter 4. The DSM is effective for capturing the complexity of a process and displaying it in a visual form that is simple for users of the information to interpret. We have reached the following conclusions about the DSM technique based on our experience with in conducting this research:

- For large complex systems and processes it can be time consuming to gather the information necessary to build a high confidence DSM. This is due to the variance in the responses one gathers from participants in the interviewing process, individual perspectives, varying levels of expertise, etc. In addition, the researcher or analyst building the DSM will invariably have to justify conflicting responses from one or more participants in the study. A lesson learned based on the attempt to build the task based Systems Engineering Process DSM was to be very careful in the data gathering phase and in choosing participants since not everyone has the knowledge and experience base from which to offer analysis.
- The result of the DSM is only a snapshot in time of the process. When the process is updated or changes for some way, the DSM will have to change also, sometimes in major ways. Accommodating this change can be very labor intensive
- The researcher must be very careful in the selection of the parameters. An incorrect set will not lead to very useful results and the concern about completeness on a very large or very complex process has to loom large in the mind of the analyst.

Several researchers at MIT are working to address some of these difficulties.[43] They have proposed a web-based "distributed and asynchronous modeling approach" to reduce or eliminate some of the difficulties of data collection outlined above.

This study has is provided some extension of the state of the art in systems engineering practice and definition: The systems engineering literature (e.g. Sheard[44] and others) does not recognize the role of manufacturing in Systems Engineering. It has been our finding that the literature on systems engineering organizations and practice focuses heavily on dealing with the technical issues that arise during the product development process, and does not include the view from the shop floor. The P&W Systems Engineering Process is significantly different from others that have been reviewed because it explicitly takes a Manufacturing perspective along with the other views that are more common in systems engineering processes. The reader will note such tasks as "Assess

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[43] Sabbaghian, N., Eppinger, S., Murman, E., "Product Development Process Capture and Display Using Web-Based Technologies," Unpublished working paper, MIT School of Engineering and Sloan School of Management.

[44] Ibid., Sheard

Manufacturing Process Capability, Establish Day One Sourcing, Coordinate Tooling Requirements, etc. These are real design to process/design for manufacturing tasks that the Systems Engineers are responsible for driving on each engine program. This incorporation of the Manufacturing perspective into the Systems Engineering process shows that P&W is taking an enlightened view of systems engineering and product development. We hasten to note that the Ford Product Development System also includes such tasks.

7.2 Recommendations

Four recommendations were derived from the preceding analyses. We have argued that it is the place of the Systems Engineers to serve in an integrative role in the new Module Center Structure. In order to do so, our analysis has shown that there is a need for changes in the Systems Engineering Organization and in the Systems Engineering Process. Since both are very new, having been defined and implemented only with in the last 6-18 months at the time of this writing, we feel the time is right to make these enhancements, especially since the Module Centers are just being put in place at this time also.

Recommendation 1: Addition of the Glue Role Systems Engineer

While the component design teams can design their component in moderate isolation from the other teams, a significant amount of coordination between components is still required. We recommend the addition of the "Glue Role" Systems Engineer within the Systems Engineering Groups that provides the daily systems engineering direction and focus for the component teams in the Module Centers. Among other tasks, these engineers would be responsible for requirement management for each component, would deal with the interface issues that arise between components, and would coordinate the flow of information between the components to ensure that there is a continuous focus on systems integration issues within the Module Centers.

Recommendation 2: Add integration tasks in the Systems Engineering Process

Our evaluation of the Systems Engineering Process, in conjunction with the DSM analysis of the design, leads us to recommend that the Systems Engineering Process explicitly include design integration tasks in each phase of the development process to address the risk identification and "technical conscience" needs of the program.

The Systems Engineering Process currently has one task called "Identify Risk Management Issues" that resides in the Concept Phase. It also has an "Enabler" task (a task that is continuous) called "Risk Management". These activities must be encouraged as continuous, not discrete events that happen once or occasionally during the design process. They should be daily activities managed by the Systems Engineers as they coordinate efforts among the component design teams and anticipate issues that might "fall through the cracks" causing major problems and rework downstream.

By explicitly including the "Systems Integration" tasks in the Process, it is made clear that the Systems Engineers have the shared responsibility to act as coordinators, communicators of information, boundary managers, and conflict resolution managers between component teams. This is an exceedingly critical role in the Module Centers because of the potential phase lag between the creation of information in the design process and the dissemination of that information to key people on the various component teams. Execution of the "Systems Integration" tasks will be greatly enhanced through the use of Information Technology, especially through the use of Object Oriented Database Tools such as DOORS for requirements management and Lotus Notes for information storage and retrieval.

Recommendation 3: Combine the SE under one Chief

While we recognize the value of the four systems engineering perspectives (System Design & Component Integration, Manufacturing Systems Engineering & Integration, Product Development and Validation, and Propulsion Systems Analysis & Integration), we believe that there is an organizational benefit to the creation of a single Systems Engineering Organization within P&W as shown in Figure 7-1, as opposed to the current collection of four separate Systems Engineering *Groups* reporting to four strong Chief Engineers. There are many reasons for moving to this structure, not the least of which is that Systems Engineering would be seen as equal to the other major organizational entities within the overall product development structure.

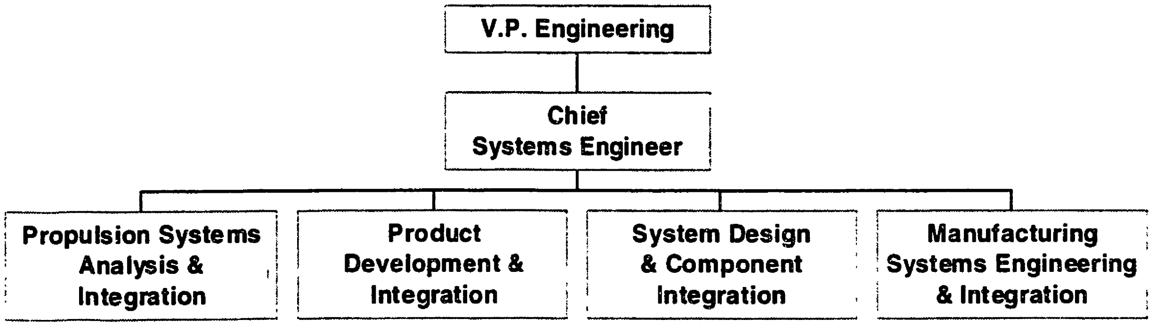

Figure 7-1
Proposed Consolidated Systems Engineering Organization, maintaining the four distinct Systems Engineering Perspectives.

Recommendation 4: Co-location during Conceptual and Preliminary Design

The fourth recommendation is associated with the Conceptual and Preliminary design phase of the engine development. Based on the system level DSM analysis we observed that the component designs can be significantly de-coupled by properly defining and managing the System Requirements and Component Requirements early in the program. These requirements must then be tracked and updated continuously. We said that a result of this virtual de-coupling was that the detailed design of the components could successfully be accomplished in a distributed manner within the Module Centers, but the integration of components through the design requirements must be managed decisively by the "Glue Role" Systems Engineers.

The Conceptual Design and Preliminary Design phases of the engine program are extremely iterative in nature. It makes sense to co-locate the Systems Engineers with Component Team members during these phases to facilitate the design trades and iterations. The deliverable from this process is a comprehensive set of System and Component Design Requirements that capture the initial target values for the system level design parameters in the System Requirements Document and the Component Requirements Document (SRD and CRD respectively).

7.3 Future Work

The study of the evolution of a product development process is intellectually rich and stimulating, especially when the focus firm is making significant organizational and process changes as P&W

has. There are a seemingly endless number of areas to be investigated; below are some suggestions for future work.

The first area of interest is the completion of a System Engineering Process DSM that was started as a part of this thesis. There are many reasons to creating the DSM of the Process. For example, the tool can help to identify the paths of communication in the Process by showing clusters of coupled tasks around the diagonal of the DSM that may be considered "meta-tasks" or "super-tasks" and that ought to belong to an individual or single group to limit the number of hand-offs and loss of control points. This may lead to a more efficient Systems Engineering Process. This activity might provide a useful test case for a simplified data gathering tool for building the DSM as proposed by Sabbaghian.[45]

Another interesting prospect for future investigation is the use of the "incidence matrix" to model the interdependencies between design parameters *and* design tasks. This could allow the investigator to more closely link the information flows of the Systems Engineering tasks and the Engine Design parameters. Kusiak proposes a method for decomposing the design process to enhance concurrency. Each task is driven by input parameters and produces output parameters. The objective is to decompose the design process into subtasks in such a manner that the interdependencies between sub-tasks are reduced. In this way concurrency in the design process can be enhanced resulting in shorter design lead-time.[46] We could envision use of this approach to more explicitly tie the Systems Engineering Process to the Conceptual/Preliminary Design Process and then cluster the resulting matrix such that the Systems Engineering Process tasks are optimally overlapped, resulting in reduced design process lead-time.

There is value in capturing the information flow of the Systems Engineering Process. The method of clustering the DSM rather than sequencing is very interesting.[47]By asking engineers how each of the engine design parameters interact using that spatial/energy/information/material attribute scale, and by surveying frequency of interaction between people on the development teams, a different view of the system design may be obtained. Cluster analysis of the resulting DSM can provide new

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[45] Ibid., Sabbaghian

[46] Ibid. Kusiak.

[47] Eppinger, S.D., "A Planning Method for Integration of Large-Scale Engineering Systems," *International Conference on Engineering Design ICED 97 Tampere*, August 19-21, 1997.

insight into the systems issues that arise during the design cycle. A final suggestion would be to extend the DSM to a Numerical-DSM as described in Yassine et al.[48]

We discussed Ford's systems engineering process, the Ford Product Development Process (FPDS) in Chapter 5. Ford is about two years ahead of P&W in definition and implementation of a process and is having growing pains with FPDS: the process is not yet universally accepted and engineers are not quite sure how the Systems Engineers and the process fit into their daily activities. P&W is now struggling with the same issues. Both Ford and P&W deal with similar product development issues: a complex product, strong functional expertise required, distributed development teams, criticality of Design for Manufacturing, aggressive Cost/Performance/Weight goals and trades during product development. It would be worthwhile for P&W to benchmark Ford's FPDS implementation process in order to facilitate the P&W Systems Engineering implementation.

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[48] Yassine, A., Falkenburg, D., Chelst, K., "Engineering Design Management: An Information Structure Approach," Accepted by the *International Journal of Production Research*, September 1998.

Bibliography

Anonymous, "Advanced Engine Programs System Analysis & Integration – New Hire Training Program", internal P&W documentation, unpublished, 1998.

Belhe, U. and Kusiak, A., "Modeling Relationships Among Design Activities," *Transactions of the ASME*, Vol. 118, December 1996, pp 454-460.

Black, Thomas A., "A System Design Approach to Automotive Brake Design", MIT MS Thesis, p26, 1990.

Clark, K., and Fujimoto, T., "Product Development Performance: Strategy, Organization, and Management in the World Auto Industry," *Harvard Business School Press*, Boston 1991.

Clausing, D., and Hauser, J., "Quality Functional Deployment," *Harvard Business Review*. 1988.

Dong, Qi, "Untitled Masters Thesis," MIT MS Thesis, February 1999.

Eppinger, S.D., "Model-based Approaches to Managing Concurrent Engineering," *Journal of Engineering Design*, Vol. 2, No. 4, pp 283-290, 1991.

Eppinger, S. D., et al., "A Model-Based Method for Organizing Tasks in Product Development," *Research in Engineering Design*, Vol. 6, pp. 1-13, 1994.

Eppinger, S.D., "A Planning Method for Integration of Large-Scale Engineering Systems," *International Conference on Engineering Design ICED 97 Tampere*, August 19-21, 1997.

Eppinger, Steven D., "Three Concurrent Engineering Problems in Product Development," MIT Sloan School of Management, Presentation given to System and Project Management Class, September 26, 1997.

Fricke, E., et al, "Modeling of Concurrent Engineering Processes for Integrated Systems Development," *Proceedings of the 17th Digital Avionics Systems Conference, Electronics in Motion*, Oct/Nov 1998, Bellevue, WA.

Gebala, D.A., Eppinger, S.D., "Methods for Analyzing Design Procedures," *Design Theory and Methodology ASME*, DE-Vol. 31, 1991, pp 227-233.

Krishnan, V., S.D. Eppinger, D. E. Whitney, "Ordering Cross-Functional Decision Making in Product Development," MIT Sloan School of Management, MIT Industrial Liaison Program, Report 2-43-93, 1993.

Krishnan, V., S.D. Eppinger, D. E. Whitney, "Overlapping Product Development Activities by Analysis of Information Transfer Practice," MIT Sloan School of Management, MIT Industrial Liaison Program Report 2-44-93, 1993

Krishnan V., Eppinger S.D., and Whitney, D.E., "Accelerating Product Development by the Exchange of Preliminary Product Design Information," *Journal of Mechanical Design*, Vol. 117, December 1995, pp 491-497.

Krishnan V., Eppinger S.D., and Whitney, D.E., "A Model-Based Framework to Overlap Product Development Activities," *Management Science*, Vol. 43, No. 4, April 1997, pp 437-451.

Kusiak, A., Wang, J., "Decomposition of the Design Process," *Journal of Mechanical Design*, Vol. 115, December 1993, pp 687-695.

Mattis, David P., "Systems Engineering Process at General Motors," MIT MS Thesis, Management of Technology Program, June 1992.

McCord, K.R., Eppinger, S. D., "Managing the Integration Problem in Concurrent Engineering," MIT Working Paper 3594-93-MSA, August 1993.

Murman, E. M., "Thoughts on System Engineering," unpublished work, Department of Aeronautics and Astronautics, MIT, September 1997.

Ross, D.T., "Structures Analysis (SA): A Language for Communicating Ideas," *IEEE Transactions on Software Engineering*, Vol. SE-3, No. 1, January 1977, pp16-34.

Sabbaghian, N., Eppinger, S., Murman, E., "Product Development Process Capture and Display Using Web-Based Technologies," Unpublished working paper, MIT School of Engineering and Sloan School of Management.

Sheard, S. A., "Twelve Systems Engineering Roles," Software Productivity Consortium, 2214 Rock Hill Rd, Herndon, VA 22070.

Smith, R.P., Eppinger, S. D., "Identifying Controlling Features of Engineering Design Iteration," *Management Science*, Vol. 43, No. 3, March 1997, p 278.

Warfield, J. N., "Binary Matrices in System Modeling," *IEEE Transactions on Systems, Man, and Cybernetics*, Vol. SMC-3, No. 5, September 1973, pp 441-449.

Yassine, A., Falkenburg, D., Chelst, K., "Engineering Design Management: An Information Structure Approach," Accepted by the *International Journal of Production Research*, September 1998.

Appendix A

This Appendix contains the precedence information used to create the Design Structure Matrices. There is a table of precedence information for each of the engine components examined in detail in this thesis.

Table A-1

Fan Precedence Information

Parameter	Precedence Information
Aircraft/Engine Range	Drag
	Thrust
By-Pass Ratio	Engine Core Flow
	Fan Airfoil Des.(Aero/Stru,H/T,AR,t/b)
	Fan Pressure Ratio
	Jet Velocity
	Propulsive Efficiency
	Total Flow
Development Cost	By-Pass Ratio
	Fan Pressure Ratio
Drag	By-Pass Ratio
	Fan Pressure Ratio
	Fan Tip Diameter
	Propulsive Efficiency
	Thrust
Emissions	Overall Pressure Ratio
Engine Core Flow	By-Pass Ratio
	Low Rotor Speed (N1)
	Total Flow
	Fan Pressure Ratio
	Fan Efficiency
Fan Airfoil Des.(Aero/Stru,H/T,AR,t/b)	Fan Tip Diameter
	Material Selection
	Number of Fan Blades
	Specific Flow (W/A)
	Fan Tip Speed
	Fan Pressure Ratio
	Fan Operability/Surge
	Total Flow
Fan Blade Containment	Fan Airfoil Des.(Aero/Stru,H/T,AR,t/b)
	Fan Tip Speed
	Low Rotor Speed (N1)
	Weight
Fan Efficiency	Fan Airfoil Des.(Aero/Stru,H/T,AR,t/b)
	Fan Operability/Surge
	Fan Tip Speed
	Propulsive Efficiency
	Specific Flow (W/A)
	Fan Gap/chord ratio
Fan Gap/chord ratio	Number of Fan Blades
	Fan Tip Diameter
	Specific Flow (W/A)
	Fan Tip Speed
Fan Operability/Surge	Fan Airfoil Des.(Aero/Stru,H/T,AR,t/b)
	Fan Efficiency
	Fan Pressure Ratio
	Fan Tip Speed
	Low Rotor Speed (N1)
	Specific Flow (W/A)
	Inlet Distortion

Table A-1

Fan Precedence Information (cont)

Parameter	Precedence Information
Fan Pressure Ratio	By-Pass Ratio
	Overall Pressure Ratio
	Propulsive Efficiency
	T4 (Combustor Exit Temperature)
	Total Flow
	Fan Operability/Surge
	Noise
Fan Tip Diameter	Fan Tip Diameter
	Fan Tip Speed
	Low Rotor Speed (N1)
	Specific Flow (W/A)
	Total Flow
	Fan Hub/Tip Ratio
Fan Tip Speed	Fan Blade Containment
	Fan Pressure Ratio
	Fan Tip Diameter
	Low Rotor Speed (N1)
	Fan Hub/Tip Ratio
HPC Pressure Ratio	By-Pass Ratio
	Overall Pressure Ratio
HPT Expansion Ratio	By-Pass Ratio
	Overall Pressure Ratio
Low Rotor Speed (N1)	By-Pass Ratio
	Fan Airfoil Des.(Aero/Stru,H/T,AR,t/b)
	Fan Efficiency
	Fan Operability/Surge
	Fan Tip Diameter
	Fan Tip Speed
LPC Diameter (Inlet/Exit)	By-Pass Ratio
	Fan Tip Diameter
	Fan Hub/Tip Ratio
LPT Expansion Ratio	By-Pass Ratio
	Overall Pressure Ratio
Maintenance Cost	Fan Airfoil Des.(Aero/Stru,H/T,AR,t/b)
	Overall Pressure Ratio
	Specific Flow (W/A)
	Thrust
Material Selection	Overall Pressure Ratio
Noise	By-Pass Ratio
	Fan Pressure Ratio
	Fan Tip Speed
	Number of Fan Blades
	Number of FEGV
	Thrust
Number of Fan Blades	Fan Airfoil Des.(Aero/Stru,H/T,AR,t/b)
	Fan Gap/chord ratio
	Low Rotor Speed (N1)
Overall Pressure Ratio	High-Low Spool Work Split
Production Cost	By-Pass Ratio
	Fan Airfoil Des.(Aero/Stru,H/T,AR,t/b)
	Fan Pressure Ratio
	Overall Pressure Ratio
	Specific Flow (W/A)
	Thrust

Table A-1
Fan Precedence Information (cont)

Parameter	Precedence Information
Propulsive Efficiency	By-Pass Ratio
	T4 (Combustor Exit Temperature)
Specific Flow (W/A)	Thrust
	Total Flow
	Maximum Flow Point
T3 (HPC Exit Temperature)	Overall Pressure Ratio
	Overall Pressure Ratio
T4 (Combustor Exit Temperature)	Overall Pressure Ratio
Thermal Efficiency	Fan Efficiency
	Overall Pressure Ratio
	T4 (Combustor Exit Temperature)
Thrust	By-Pass Ratio
	Drag
	Fan Airfoil Des.(Aero/Stru,H/T,AR,t/b)
	Fan Pressure Ratio
	Low Rotor Shaft Torque
	Propulsive Efficiency
	Specific Flow (W/A)
Total Flow	By-Pass Ratio
	Engine Core Flow
	Fan Operability/Surge
	Fan Pressure Ratio
	Low Rotor Shaft Torque
	Low Rotor Speed (N1)
	LPT Stage Count
	Propulsive Efficiency
	Thrust
TSFC	By-Pass Ratio
	Fan Efficiency
	Fan Pressure Ratio
	Overall Pressure Ratio
	Propulsive Efficiency
Weight	By-Pass Ratio
	Fan Airfoil Des.(Aero/Stru,H/T,AR,t/b)
	Fan Blade Containment
	Fan Pressure Ratio
	Fan Tip Diameter

Table A-2

LPC Precedence Information

Parameter	Precedence Information
By-Pass Ratio	Total Flow
Engine Core Flow	High-Low Spool Work Split
	HPC Diameter (Inlet/Exit)
	HPC Efficiency
	HPC Operability (Surge Margin)
	HPC Pressure Ratio
	HPC Stage Count
	Low Rotor Speed (N1)
	LPC Diameter (Inlet/Exit)
	LPC Stage Count
	Total Flow
	LPC Pressure Ratio (work)
	LPC Efficiency
High-Low Spool Work Split	Engine Core Flow
	HPC Diameter (Inlet/Exit)
	HPC Efficiency
	HPC Pressure Ratio
	HPC Stage Count
	LPC Pressure Ratio (work)
HPT Blade Tip Clearance	LPC Bleeds (Config. & Flows, Cust/TCA)
Low Rotor Shaft Critical Speed	LPC Axial Gapping
	LPC Length
	LPC Stage Count
Low Rotor Shaft Design	LPC Length
Low Rotor Speed (N1)	Engine Core Flow
	High-Low Spool Work Split
	LPC Airfoil Des.(Aero/Stru,H/T,AR,t/b)
	LPC Diameter (Inlet/Exit)
	LPC Disk/Drum Design
	LPC Operability (Surge Margin)
	LPC Pressure Ratio (work)
	LPC Stage Count
LPC Airfoil Counts	Low Rotor Speed (N1)
	LPC Stage Count
	LPC Pressure Ratio (work)
LPC Airfoil Des.(Aero/Stru,H/T,AR,t/b)	Low Rotor Speed (N1)
	LPC Disk/Drum Design
	LPC Pressure Ratio (work)
	LPC Stage Count
	Material Selection
LPC Axial Gapping	Low Rotor Shaft Critical Speed
	LPC Efficiency
	Reliability (Engine System)
	Reliability (Engine System)
LPC Blade Tip Clearance	LPC Efficiency
	LPC Operability (Surge Margin)
LPC Bleeds (Config. & Flows, Cust/TCA)	LPC Efficiency
	LPC Operability (Surge Margin)
	Production Cost
	Reliability (Engine System)
LPC Diameter (Inlet/Exit)	By-Pass Ratio
	Low Rotor Speed (N1)
	Fan Tip Diameter

Table A-2
LPC Precedence Information (cont.)

Parameter	Precedence Information
LPC Disk/Drum Design	High Rotor Speed (N2)
	Low Rotor Speed (N1)
	Material Selection
	Production Cost
	Weight
LPC Efficiency	High-Low Spool Work Split
	LPC Airfoil Des.(Aero/Stru,H/T,AR,t/b)
	LPC Bleeds (Config. & Flows, Cust/TCA)
	LPC Length
	LPC Operability (Surge Margin)
LPC Length	Bearing Locations and Compartments L/O
	Low Rotor Shaft Critical Speed
	Low Rotor Speed (N1)
	LPC Airfoil Des.(Aero/Stru,H/T,AR,t/b)
	LPC Stage Count
	LPC Stage Count
	Rotor Support System
	Weight
LPC Operability (Surge Margin)	Low Rotor Speed (N1)
	LPC Airfoil Des.(Aero/Stru,H/T,AR,t/b)
	LPC Efficiency
	LPC Pressure Ratio (work)
	LPC Stage Count
LPC Pressure Ratio (work)	High-Low Spool Work Split
	Low Rotor Speed (N1)
	LPC Airfoil Des.(Aero/Stru,H/T,AR,t/b)
	LPC Operability (Surge Margin)
LPC Stage Count	By-Pass Ratio
	Engine Core Flow
	High-Low Spool Work Split
	Low Rotor Shaft Critical Speed
	LPC Airfoil Des.(Aero/Stru,H/T,AR,t/b)
	LPC Disk/Drum Design
	LPC Efficiency
	LPC Operability (Surge Margin)
	LPC Pressure Ratio (work)
	Overall Pressure Ratio
	LPC Pressure Ratio (work)
	LPC Operability (Surge Margin)
	LPC Airfoil Des.(Aero/Stru,H/T,AR,t/b)
	Low Rotor Speed (N1)
	LPC Diameter (Inlet/Exit)
LPT BladeTip Clearance	LPC Diameter (Inlet/Exit)
LPT Case Cooling	LPC Bleeds (Config. & Flows, Cust/TCA)
LPT Velocity Ratio	LPT Diameter (Inlet/Exit)
Maintenance Cost	LPC Airfoil Counts
	LPC Airfoil Des.(Aero/Stru,H/T,AR,t/b)
	LPC Length
	LPC Stage Count
Material Selection	LPC Airfoil Des.(Aero/Stru,H/T,AR,t/b)
Noise	LPC Axial Gapping
Overall Pressure Ratio	LPC Stage Count

Table A-2
LPC Precedence Information (cont.)

Parameter	Precedence Information
Production Cost	LPC Airfoil Counts
	LPC Airfoil Des.(Aero/Stru,H/T,AR,t/b)
	LPC Length
	LPC Stage Count
Reliability (Engine System)	LPC Operability (Surge Margin)
T4 (Combustor Exit Temperature)	LPC Bleeds (Config. & Flows, Cust/TCA)
Thermal Management Subsystems	LPC Bleeds (Config. & Flows, Cust/TCA)
TSFC	LPC Bleeds (Config. & Flows, Cust/TCA)
Weight	LPC Airfoil Counts
	LPC Airfoil Des.(Aero/Stru,H/T,AR,t/b)
	LPC Length
	LPC Stage Count

Table A-3
HPC Precedence Information

Parameter	**Precedence Information**
Bearing Locations and Compartments L/O	HPC Length
Combustor Temperature	Engine Core Flow
	HPC Exit Pres/Temp Profile
Durability/Life	HPC Axial Gapping
Emissions	T3 (HPC Exit Temperature)
Engine Core Flow	High-Low Spool Work Split
	HPC Diameter (Inlet/Exit)
	HPC Efficiency
	HPC Operability (Surge Margin)
	HPC Pressure Ratio
	HPC Stage Count
	Total Flow
High Rotor Speed (N2)	High-Low Spool Work Split
	HPC Efficiency
	HPC Operability (Surge Margin)
High-Low Spool Work Split	Engine Core Flow
	HPC Diameter (Inlet/Exit)
	HPC Efficiency
	HPC Operability (Surge Margin)
	HPC Pressure Ratio
	HPC Stage Count
	LPC Pressure Ratio (work)
HPC Airfoil Counts	High Rotor Speed (N2)
	HPC Pressure Ratio
	HPC Stage Count
HPC Airfoil Des.(Aero/Stru,H/T,AR,t/b)	High Rotor Speed (N2)
	HPC Airfoil Counts
	HPC Axial Gapping
	HPC Efficiency
	HPC Operability (Surge Margin)
	HPC Pressure Ratio
	Material Selection
HPC Axial Gapping	HPC Efficiency
	Reliability (Engine System)
HPC Blade Root Stress (Limiting)	High Rotor Speed (N2)
	HPC Airfoil Des.(Aero/Stru,H/T,AR,t/b)
	T4 (Combustor Exit Temperature)
HPC Bleeds (Config. & Flows, Cust/TCA)	Durability/Coatings Selection
	HPC Efficiency
	HPC Operability (Surge Margin)
	HPC Pressure Ratio
	Production Cost
	Reliability (Engine System)
HPC Case Design	HPC Bleeds (Config. & Flows, Cust/TCA)
	HPC Diameter (Inlet/Exit)
	HPC Operability (Surge Margin)
	HPC Tip Clearance

Table A-3
HPC Precedence Information (cont.)

Parameter	Precedence Information
HPC Disk/Drum Design	High Rotor Speed (N2)
	Low Rotor Shaft Design
	Material Selection
	Production Cost
	Weight
HPC Efficiency	High-Low Spool Work Split
	HPC Airfoil Des.(Aero/Stru,H/T,AR,t/b)
	HPC Bleeds (Config. & Flows, Cust/TCA)
	HPC Operability (Surge Margin)
	HPC Pressure Ratio
	HPC Tip Clearance
HPC Exit Pres/Temp Profile	HPC Airfoil Des.(Aero/Stru,H/T,AR,t/b)
	HPC Efficiency
	T3 (HPC Exit Temperature)
HPC Length	HPC Airfoil Des.(Aero/Stru,H/T,AR,t/b)
	HPC Axial Gapping
	HPC Case Design
	HPC Stage Count
	Low Rotor Shaft Critical Speed
	Weight
HPC Operability (Surge Margin)	HPC Airfoil Des.(Aero/Stru,H/T,AR,t/b)
	HPC Bleeds (Config. & Flows, Cust/TCA)
	HPC Efficiency
	HPC Pressure Ratio
	HPC Tip Clearance
HPC Pressure Ratio	Aircraft/Engine Range
	By-Pass Ratio
	High-Low Spool Work Split
	HPC Airfoil Des.(Aero/Stru,H/T,AR,t/b)
	HPC Diameter (Inlet/Exit)
	HPC Efficiency
	HPC Operability (Surge Margin)
	HPC Stage Count
	Overall Pressure Ratio
	T4 (Combustor Exit Temperature)
	Total Flow
HPC Stage Count	High Rotor Speed (N2)
	HPC Airfoil Des.(Aero/Stru,H/T,AR.t/b)
	HPC Axial Gapping
	HPC Case Design
	HPC Diameter (Inlet/Exit)
	HPC Efficiency
	HPC Operability (Surge Margin)
	HPC Pressure Ratio
	HPC Tip Clearance
	Overall Pressure Ratio
HPC Tip Clearance	HPC Case Design
	HPC Efficiency
	Rotor Support System

Table A-3

HPC Precedence Information (cont.)

Parameter	Precedence Information
Low Rotor Shaft Critical Speed	HPC Length
Low Rotor Shaft Design	HPC Length
	T3 (HPC Exit Temperature)
Maintenance Cost	Durability/Coatings Selection
	HPC Airfoil Des.(Aero/Stru,H/T,AR,t/b)
	HPC Case Design
	HPC Stage Count
	Variable Geometry Configuration
Material Selection	HPC Airfoil Des.(Aero/Stru,H/T,AR,t/b)
	HPC Disk/Drum Design
Production Cost	HPC Airfoil Des.(Aero/Stru,H/T,AR,t/b)
	HPC Case Design
	HPC Pressure Ratio
	HPC Stage Count
	Variable Geometry Configuration
Reliability (Engine System)	HPC Axial Gapping
	Variable Geometry Configuration
Rotor Support System	HPC Case Design
T3 (HPC Exit Temperature)	Combustor Temperature
	Engine Core Flow
	HPC Airfoil Des.(Aero/Stru,H/T,AR,t/b)
	HPC Efficiency
	HPC Pressure Ratio
	Overall Pressure Ratio
Thermal Efficiency	HPC Efficiency
Thermal Management Subsystems	HPC Bleeds (Config. & Flows, Cust/TCA)
TSFC	HPC Exit Pres/Temp Profile
	T3 (HPC Exit Temperature)
	Total Flow
	Variable Geometry Configuration
Turbine Cooling Air	T3 (HPC Exit Temperature)
Variable Geometry Configuration	HPC Operability (Surge Margin)
	HPC Pressure Ratio
Weight	HPC Airfoil Des.(Aero/Stru,H/T,AR,t/b)
	HPC Pressure Ratio
	HPC Stage Count
	Variable Geometry Configuration

Table A-4
Diffuser/Combustor Precedence Information

Parameter	Precedence Information
Combustor Pressure Loss	Thermal Management Subsystems
	Turbine Cooling Air
	Emissions
	Combustor Exit Temperature Uniformity
	Durability/Life
	Durability/Coatings Selection
Combustor Temperature	HPC Exit Pres/Temp Profile
	Overall Pressure Ratio
	Durability/Coatings Selection
	Durability/Life
Diffuser Delta Pressure Recovery	Diffuser/Combustor Length
	Engine Core Flow
	Overall Pressure Ratio
Diffuser/Combustor Length	Bearing Locations and Compartments L/O
	Emissions
	Weight
	Durability/Life
	Emissions
	Engine Core Flow
	Diffuser Delta Pressure Recovery
Durability/Coatings Selection	Combustor Pressure Loss
	Material Selection
	Production Cost
	Combustor Temperature
Emissions	Combustor Pressure Loss
	Combustor Temperature
	Diffuser/Combustor Length
	Overall Pressure Ratio
	T3 (HPC Exit Temperature)
	T4 (Combustor Exit Temperature)
Engine Core Flow	Combustor Pressure Loss
	Combustor Temperature
HPC Pressure Ratio	T4 (Combustor Exit Temperature)
Low Rotor Shaft Critical Speed	Diffuser/Combustor Length
	Diffuser Structural Stiffness
Low Rotor Shaft Design	Diffuser/Combustor Length
Maintenance Cost	T4 (Combustor Exit Temperature)
	Durability/Life
	HPC Exit Pres/Temp Profile
	Material Selection
	T3 (HPC Exit Temperature)
	T4 (Combustor Exit Temperature)

Table A-4

Diffuser/Combustor Precedence Information (cont.)

Parameter	Precedence Information
Production Cost	T4 (Combustor Exit Temperature)
	Durability/Coatings Selection
	Material Selection
	Total Flow
	Turbine Cooling Air
Seal Design	Diffuser/Combustor Length
	Bearing Technology (DN)
	High Rotor Speed (N2)
	HPC Pressure Ratio
	Production Cost
T3 (HPC Exit Temperature)	Overall Pressure Ratio
T4 (Combustor Exit Temperature)	Engine Core Flow
	HPC Bleeds (Config. & Flows, Cust/TCA)
	LPC Bleeds (Config. & Flows, Cust/TCA)
	Overall Pressure Ratio
	Turbine Cooling Air
	TSFC
	Combustor Efficiency
TSFC	T4 (Combustor Exit Temperature)
	Combustor Pressure Loss
Turbine Cooling Air	T3 (HPC Exit Temperature)
	T4 (Combustor Exit Temperature)
	Combustor Exit Temperature Uniformity
	Material Selection
Weight	Diffuser/Combustor Length
	T4 (Combustor Exit Temperature)
	Material Selection
	HPC Pressure Ratio
	Diffuser Delta Pressure Recovery
	T4 (Combustor Exit Temperature)
	Durability/Life

Table A-5
HPT Precedence Information

Parameter	Precedence Information
Durability/Coatings Selection	Combustor Pressure Loss
	HPT AN^2
	Material Selection
	Turbine Cooling Air
Durability/Life	HPT Airfoil Design
Emissions	T4 (Combustor Exit Temperature)
Engine Core Flow	HPT Efficiency
	HPT Expansion Ratio
	T4 (Combustor Exit Temperature)
High Rotor Speed (N2)	HPT AN^2
	HPT Efficiency
HPC Bleeds (Config. & Flows, Cust/TCA)	Durability/Coatings Selection
	HPT Airfoil Design
HPT Airfoil Counts	High Rotor Speed (N2)
	HPT AN^2
	HPT Efficiency
	HPT Length
	HPT Stage Count
	Maintenance Cost
	Production Cost
	Weight
HPT Airfoil Design	Development Cost
	Engine Core Flow
	HPC Bleeds (Config. & Flows, Cust/TCA)
	HPT AN^2
	HPT Efficiency
	Maintenance Cost
	Material Selection
	Production Cost
	T3 (HPC Exit Temperature)
	T4 (Combustor Exit Temperature)
HPT AN^2	HPT Stage Count
HPT Blade Root Stress (Limiting)	Engine Core Flow
	HPT Airfoil Design
	HPT AN^2
	HPT Disk Design
HPT Blade Tip Clearance	HPT AN^2
	HPT Disk Design
	Rotor Support System
	Turbine Cooling Air

Table A-5
HPT Precedence Information (cont.)

Parameter	Precedence Information
HPT Disk Design	High Rotor Speed (N2)
	HPC Bleeds (Config. & Flows, Cust/TCA)
	HPT Length
	Low Rotor Shaft Design
	Material Selection
	Production Cost
	Rotor Support System
	Weight
HPT Efficiency	HPT Blade Tip Clearance
	HPT Expansion Ratio
	HPT Stage Count
	HPT Velocity Ratio
	Turbine Cooling Air
HPT Expansion Ratio	By-Pass Ratio
	Engine Core Flow
	HPT AN^2
	Overall Pressure Ratio
	Turbine Cooling Air
HPT Flow Parameter	HPT AN^2
HPT Length	Bearing Locations and Compartments L/O
	HPT Stage Count
	Low Rotor Shaft Critical Speed
	Low Rotor Shaft Torque
	Rotor Support System
	Weight
HPT Stage Count	High Rotor Speed (N2)
	HPT AN^2
	HPT Expansion Ratio
HPT Velocity Ratio	HPT Airfoil Counts
	HPT AN^2
	HPT Expansion Ratio
Low Rotor Shaft Critical Speed	HPT Length
Low Rotor Shaft Design	HPT Length

Table A-5
HPT Precedence Information (cont.)

Parameter	Precedence Information
LPC Disk/Drum Design	Weight
LPT Expansion Ratio	By-Pass Ratio
	HPT Flow Parameter
	Overall Pressure Ratio
	Turbine Cooling Air
LPT Velocity Ratio	HPT Flow Parameter
Maintenance Cost	HPT Airfoil Counts
	HPT Airfoil Design
	HPT Stage Count
	Material Selection
	T4 (Combustor Exit Temperature)
Material Selection	Engine Core Flow
	High Rotor Speed (N2)
	HPT Airfoil Design
	HPT AN^2
	HPT Disk Design
	Maintenance Cost
	Production Cost
	T3 (HPC Exit Temperature)
	T4 (Combustor Exit Temperature)
	Weight

Table A-5
HPT Precedence Information (cont.)

Parameter	Precedence Information
Production Cost	Engine Core Flow
	HPT Airfoil Counts
	HPT Airfoil Design
	HPT AN^2
	HPT Disk Design
	HPT Length
	HPT Stage Count
	Material Selection
	T4 (Combustor Exit Temperature)
Reliability (Engine System)	Durability/Coatings Selection
	Durability/Life
	HPT Airfoil Design
	HPT AN^2
	HPT Blade Tip Clearance
	Turbine Cooling Air
Rotor Support System	HPT Blade Tip Clearance
	Low Rotor Shaft Critical Speed
T4 (Combustor Exit Temperature)	Engine Core Flow
	HPC Bleeds (Config. & Flows, Cust/TCA)
	LPC Bleeds (Config. & Flows, Cust/TCA)
	Overall Pressure Ratio
	Reliability (Engine System)
	Turbine Cooling Air
Thermal Efficiency	HPT Efficiency
	T4 (Combustor Exit Temperature)
Thermal Management Subsystems	HPC Bleeds (Config. & Flows, Cust/TCA)
TSFC	HPT Blade Tip Clearance
	HPT Velocity Ratio
	T4 (Combustor Exit Temperature)
Turbine Cooling Air	Engine Core Flow
	High Rotor Speed (N2)
	HPT Efficiency
	HPT Expansion Ratio
	Low Rotor Speed (N1)
	LPT Expansion Ratio
	T3 (HPC Exit Temperature)
	T4 (Combustor Exit Temperature)
Weight	HPT Airfoil Counts
	HPT Length
	HPT Stage Count
	T4 (Combustor Exit Temperature)
Durability/Coatings Selection	HPC Bleeds (Config. & Flows, Cust/TCA)

Table A-6
LPT Precedence Information

Parameter	Precedence Information
Bearing Locations and Compartments L/O	HPT Disk Design
	Low Rotor Shaft Critical Speed
	Low Rotor Shaft Design
	LPT BladeTip Clearance
Bearing Reliability	Low Rotor Shaft Critical Speed
Bearing Technology (DN)	Low Rotor Shaft Critical Speed
	Low Rotor Shaft Design
By-Pass Ratio	Jet Velocity
Diffuser/Combustor Length	Low Rotor Shaft Torque
Engine Core Flow	LPT Diameter (Inlet/Exit)
High-Low Spool Work Split	By-Pass Ratio
	Engine Core Flow
	LPT Stage Count
	Overall Pressure Ratio
HPC Disk/Drum Design	Low Rotor Shaft Design
HPC Length	Low Rotor Shaft Critical Speed
	Low Rotor Shaft Torque
HPT Disk Design	Low Rotor Shaft Design
HPT Length	Low Rotor Shaft Critical Speed
	Low Rotor Shaft Torque
Low Rotor Shaft Critical Speed	Bearing Locations and Compartments L/O
	Diffuser/Combustor Length
	HPC Length
	HPT Length
	Low Rotor Shaft Design
	Low Rotor Speed (N1)
	LPC Axial Gapping
	LPC Stage Count
	LPT Length
	LPT Stage Count
	Material Selection
Low Rotor Shaft Design	Bearing Locations and Compartments L/O
	Bearing Locations and Compartments L/O
	Diffuser/Combustor Length
	HPC Length
	HPT Length
	Low Rotor Shaft Critical Speed
	Low Rotor Shaft Torque
	Low Rotor Speed (N1)
	LPT Length
	Material Selection
	Production Cost
	T3 (HPC Exit Temperature)
	T3 (HPC Exit Temperature)
Low Rotor Shaft Torque	Low Rotor Speed (N1)
	LPT Expansion Ratio
Low Rotor Speed (N1)	High-Low Spool Work Split
	LPT BladeTip Clearance
	LPT Efficiency
LPC Axial Gapping	Low Rotor Shaft Critical Speed
LPC Length	Low Rotor Shaft Critical Speed
LPC Stage Count	Low Rotor Shaft Critical Speed
LPT Airfoil Counts	Low Rotor Speed (N1)
	LPT Stage Count

Table A-6

LPT Precedence Information (cont.)

Parameter	Precedence Information
LPT Airfoil Des.(Aero/Stru,H/T,AR,t/b)	Material Selection
	Production Cost
LPT BladeTip Clearance	Low Rotor Speed (N1)
	LPT Case Cooling
	Rotor Support System
LPT Case Cooling	HPC Bleeds (Config. & Flows, Cust/TCA)
	LPC Bleeds (Config. & Flows, Cust/TCA)
	LPT Efficiency
LPT Diameter (Inlet/Exit)	Engine Core Flow
LPT Diameter (Inlet/Exit)	LPT BladeTip Clearance
LPT Disk Design	Low Rotor Speed (N1)
	LPT BladeTip Clearance
	Material Selection
	Production Cost
	Weight
LPT Efficiency	LPT BladeTip Clearance
	LPT Case Cooling
	LPT Expansion Ratio
	LPT Stage Count
	LPT Velocity Ratio
LPT Expansion Ratio	By-Pass Ratio
	HPT Flow Parameter
	Overall Pressure Ratio
	Turbine Cooling Air
LPT Length	Bearing Locations and Compartments L/O
	Low Rotor Shaft Critical Speed
	Rotor Support System
	Weight
LPT Stage Count	Low Rotor Shaft Critical Speed
	Low Rotor Speed (N1)
LPT Velocity Ratio	HPT Flow Parameter
	Low Rotor Speed (N1)
	LPT Diameter (Inlet/Exit)
	LPT Stage Count
Maintenance Cost	LPT Airfoil Counts
Noise	LPT Airfoil Counts
	LPT Length
Production Cost	LPT Airfoil Counts
Propulsive Efficiency	LPT Stage Count
Rotor Support System	Low Rotor Shaft Critical Speed
	LPT BladeTip Clearance
Thermal Efficiency	LPT Efficiency
Thrust	Low Rotor Shaft Torque
	LPT Stage Count
Total Flow	Low Rotor Shaft Torque
	LPT Stage Count
Turbine Cooling Air	High Rotor Speed (N2)
	Low Rotor Speed (N1)
	LPT Expansion Ratio
Weight	LPT Airfoil Counts

Table A-7
Mechanical Components Precedence Information

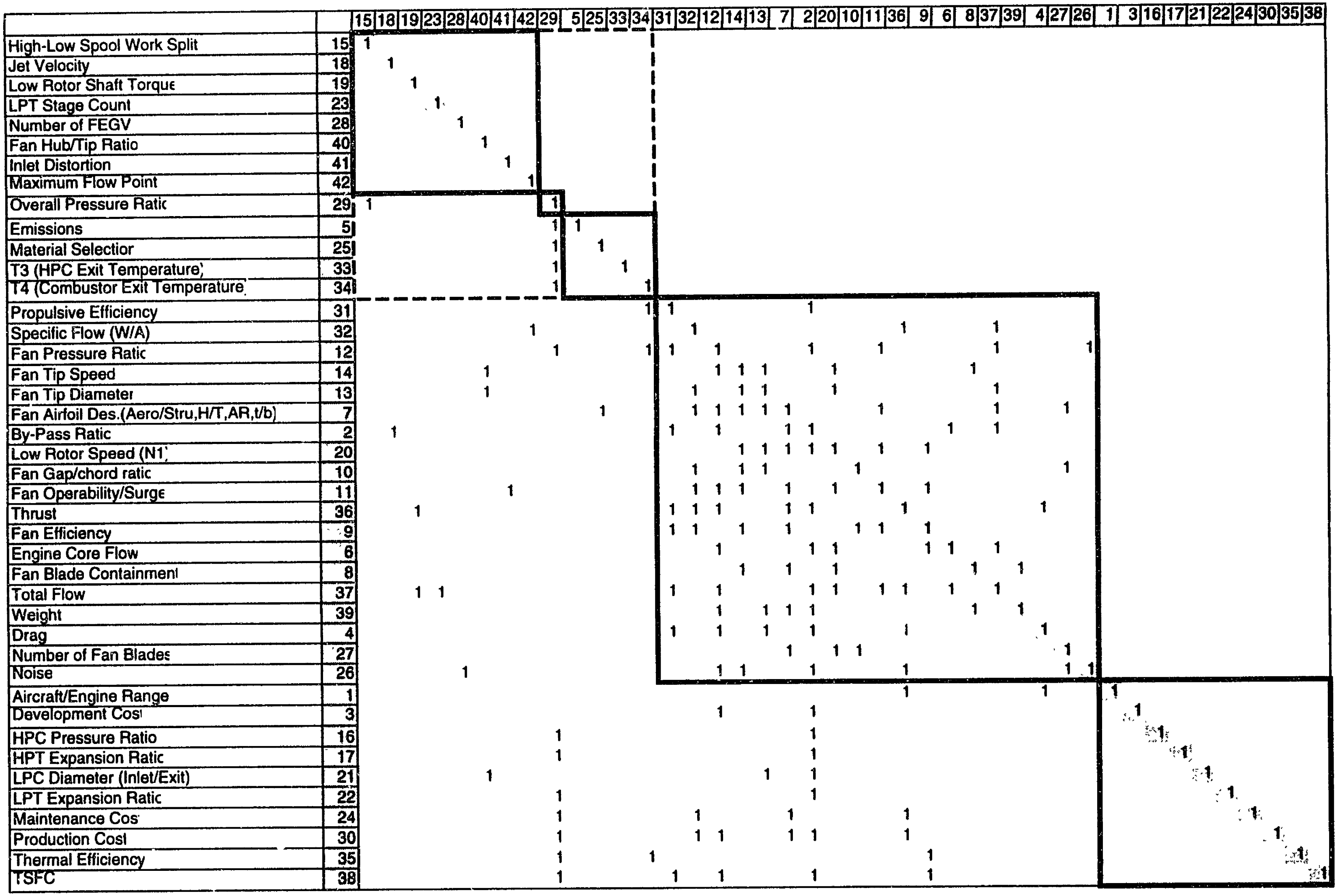
Parameter	Precedence Information
Bearing Locations and Compartments L/O	HPC Case Design
	Low Rotor Shaft Critical Speed
	Low Rotor Shaft Design
	LPT BladeTip Clearance
	Rotor Support System
Bearing Reliability	Bearing Technology (DN)
	High Rotor Speed (N2)
	Low Rotor Shaft Critical Speed
	Oil & Lube System
Bearing Technology (DN)	Bearing Reliability
	Seal Design
	High Rotor Speed (N2)
	Low Rotor Shaft Critical Speed
	Low Rotor Shaft Design
	Low Rotor Speed (N1)
Seal Design	Bearing Technology (DN)
	High Rotor Speed (N2)
	Low Rotor Speed (N1)
	Material Selection
Development Cost	Rotor Support System
Diffuser/Combustor Length	Bearing Locations and Compartments L/O
	Rotor Support System
High Rotor Speed (N2)	Bearing Technology (DN)
	Seal Design
	Rotor Support System
HPC Length	Bearing Locations and Compartments L/O
	Rotor Support System
HPC Tip Clearance	Rotor Support System
HPT Length	Bearing Locations and Compartments L/O
	Rotor Support System
Low Rotor Shaft Critical Speed	Bearing Locations and Compartments L/O
	Bearing Technology (DN)
Low Rotor Shaft Design	Bearing Locations and Compartments L/O
	Bearing Technology (DN)
Low Rotor Speed (N1)	Bearing Reliability
	Bearing Technology (DN)
	Seal Design
	Rotor Support System
LPC Length	Bearing Locations and Compartments L/O
	Rotor Support System
LPT BladeTip Clearance	Rotor Support System
LPT Length	Bearing Locations and Compartments L/O
	Rotor Support System
Oil & Lube System	Bearing Locations and Compartments L/O
	Bearing Reliability
Rotor Support System	HPC Case Design
	HPT Blade Tip Clearance
	Low Rotor Shaft Critical Speed
	LPT BladeTip Clearance

Appendix B

Design Structures Matrices for the Engine Components examined in this thesis.

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
Aircraft/Engine Range	1	1			1																																1						
By-Pass Ratio	2		1				1	1					1						1													1						1					
Development Cost	3		1	1									1																														
Drag	4		1		1								1	1																		1					1						
Emissions	5					1																								1													
Engine Core Flow	6		1				1			1			1								1																	1					
Fan Airfoil Des.(Aero/Stru,H/T,AR,t/b)	7							1				1	1	1	1											1		1					1					1					
Fan Blade Containment	8							1	1						1						1																			1			
Fan Efficiency	9							1		1	1	1			1																	1	1										
Fan Gap/chord ratio	10										1			1	1													1					1										
Fan Operability/Surge	11							1		1		1	1		1						1												1									1	
Fan Pressure Ratio	12		1									1	1														1			1		1			1			1					
Fan Tip Diameter	13													1	1						1												1					1			1		
Fan Tip Speed	14								1				1	1	1						1																				1		
High-Low Spool Work Split	15															1																											
HPC Pressure Ratio	16		1														1													1													
HPT Expansion Ratio	17		1															1												1													
Jet Velocity	18																		1																								
Low Rotor Shaft Torque	19																			1																							
Low Rotor Speed (N1)	20		1					1		1		1		1	1						1																						
LPC Diameter (Inlet/Exit)	21		1											1								1																			1		
LPT Expansion Ratio	22		1																				1							1													
LPT Stage Count	23																							1																			
Maintenance Cost	24							1																	1					1			1				1						
Material Selection	25																									1				1													
Noise	26		1										1		1												1	1	1								1						
Number of Fan Blades	27							1			1										1							1															
Number of FEGV	28																												1														
Overall Pressure Ratio	29															1														1													
Production Cost	30		1					1					1																	1	1		1				1						
Propulsive Efficiency	31		1																													1			1								
Specific Flow (W/A)	32																																1				1	1					1
T3 (HPC Exit Temperature)	33																													1				1									
T4 (Combustor Exit Temperature	34																													1					1								
Thermal Efficiency	35									1																				1					1	1							
Thrust	36		1		1			1					1							1												1	1				1						
Total Flow	37		1				1					1	1							1	1			1								1					1	1					
TSFC	38		1							1			1																	1		1							1				
Weight	39		1					1	1				1	1																										1			
Fan Hub/Tip Ratio	40																																								1		
Inlet Distortion	41																																									1	
Maximum Flow Point	42																																										1

Figure B-1
Fan Unpartitioned DSM



		15	18	19	23	28	40	41	42	29	5	25	33	34	31	32	12	14	13	7	2	20	10	11	36	9	6	8	37	39	4	27	26	1	3	16	17	21	22	24	30	35	38
High-Low Spool Work Split	15	1																																									
Jet Velocity	18		1																																								
Low Rotor Shaft Torque	19			1																																							
LPT Stage Count	23				1																																						
Number of FEGV	28					1																																					
Fan Hub/Tip Ratio	40						1																																				
Inlet Distortion	41							1																																			
Maximum Flow Point	42								1																																		
Overall Pressure Ratio	29	1								1																																	
Emissions	5									1	1																																
Material Selection	25									1		1																															
T3 (HPC Exit Temperature)	33									1			1																														
T4 (Combustor Exit Temperature)	34									1				1																													
Propulsive Efficiency	31													1	1							1																					
Specific Flow (W/A)	32								1							1									1				1														
Fan Pressure Ratio	12									1				1	1		1				1			1					1				1										
Fan Tip Speed	14						1										1	1				1						1															
Fan Tip Diameter	13						1									1		1	1			1							1														
Fan Airfoil Des.(Aero/Stru,H/T,AR,t/b)	7											1				1	1	1	1	1				1					1			1											
By-Pass Ratio	2		1												1		1			1	1						1		1														
Low Rotor Speed (N1)	20																	1	1	1	1	1		1		1																	
Fan Gap/chord ratio	10															1		1	1				1									1											
Fan Operability/Surge	11							1								1	1	1		1		1		1		1																	
Thrust	36			1											1	1	1			1	1				1						1												
Fan Efficiency	9														1	1		1		1			1	1		1																	
Engine Core Flow	6																1				1	1				1	1		1														
Fan Blade Containment	8																	1		1		1						1		1													
Total Flow	37			1	1										1		1				1	1		1	1		1		1														
Weight	39																1		1	1	1							1		1													
Drag	4														1		1		1		1				1						1												
Number of Fan Blades	27																			1		1	1									1											
Noise	26					1											1	1			1				1							1	1										
Aircraft/Engine Range	1																								1						1			1									
Development Cost	3																1				1														1								
HPC Pressure Ratio	16									1											1															1							
HPT Expansion Ratio	17									1											1																1						
LPC Diameter (Inlet/Exit)	21						1												1		1																	1					
LPT Expansion Ratio	22									1											1																		1				
Maintenance Cost	24									1						1				1					1															1			
Production Cost	30									1						1	1			1	1				1																1		
Thermal Efficiency	35									1				1												1																1	
TSFC	38									1					1		1				1					1																	1

Figure B-2
Fan Partitioned DSM

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43
Bearing Locations and Compartments L/C	1	1																																										
By-Pass Ratic	2		1																																							1		
Engine Core Flow	3			1			1	1	1	1	1	1				1						1		1			1	1														1		
Fan Tip Diametei	4				1																																							
High Rotor Speed (N2'	5					1																																						
High-Low Spool Work Split	6			1			1	1	1		1	1															1																	
HPC Diameter (Inlet/Exit)	7							1																																				
HPC Efficiency	8								1																																			
HPC Operability (Surge Margin'	9									1																																		
HPC Pressure Ratic	10										1																																	
HPC Stage Count	11											1																																
HPT Blade Tip Clearance	12												1								1																							
Low Rotor Shaft Critical Speec	13													1				1							1			1																
Low Rotor Shaft Desigr	14														1										1																			
Low Rotor Speed (N1'	15			1			1									1	1					1	1			1	1	1																
LPC Airfoil Des.(Aero/Stru,H/T,AR,t/b)	16															1	1						1				1	1						1										
LPC Axial Gapping	17													1				1						1														1						
LPC Airfoil Counts	18															1			1								1	1																
LPC Blade Tip Clearance	19																			1				1		1																		
LPC Bleeds (Config. & Flows, Cust/TCA)	20																				1			1		1											1	1						
LPC Diameter (Inlet/Exit)	21		1		1											1						1																						
LPC Disk/Drum Design	22					1										1							1											1			1							1
LPC Efficiency	23						1										1				1			1	1	1																		
LPC Length	24	1												1		1	1								1			1											1					1
LPC Operability (Surge Margin'	25															1	1							1		1	1	1																
LPC Pressure Ratio (work	26						1									1	1									1	1																	
LPC Stage Count	27		1	1			1							1		1	1					1	1	1		1	1	1								1								
LPT BladeTip Clearance	28																					1							1															
LPT Case Cooling	29																				1									1														
LPT Diameter (Inlet/Exit)	30																														1													
LPT Velocity Ratio	31																														1	1												
Maintenance Cos	32																1		1						1			1					1											
Material Selectior	33																1																	1										
Noise	34																	1																	1									
Overall Pressure Ratio	35																											1								1								
Production Cost	36																1		1						1			1									1							
Reliability (Engine System)	37																									1												1						
Rotor Support System	38																																						1					
T4 (Combustor Exit Temperature'	39																				1																			1				
Thermal Management Subsystems	40																				1																				1			
Total Flow	41																																									1		
TSFC	42																				1																						1	
Weight	43																1		1						1			1																1

Figure B-3
LPC Unpartitioned DSM

		1	4	5	7	8	9	10	11	30	38	41	2	31	21	6	26	33	37	16	23	15	27	18	13	17	24	43	36	3	22	25	35	19	20	12	14	28	29	32	34	39	40	42
Bearing Locations and Compartments L/O	1	1																																										
Fan Tip Diameter	4		1																																									
High Rotor Speed (N2)	5			1																																								
HPC Diameter (Inlet/Exit)	7				1																																							
HPC Efficiency	8					1																																						
HPC Operability (Surge Margin)	9						1																																					
HPC Pressure Ratio	10							1																																				
HPC Stage Count	11								1																																			
LPT Diameter (Inlet/Exit)	30									1																																		
Rotor Support System	38										1																																	
Total Flow	41											1																																
By-Pass Ratio	2											1	1																															
LPT Velocity Ratio	31									1				1																														
LPC Diameter (Inlet/Exit)	21		1										1		1							1																						
High-Low Spool Work Split	6				1	1		1	1							1	1													1														
LPC Pressure Ratio (work	26															1	1			1		1										1												
Material Selection	33																	1		1																								
Reliability (Engine System)	37																		1													1												
LPC Airfoil Des.(Aero/Stru,H/T,AR,t/b)	16																1	1		1		1	1								1													
LPC Efficiency	23															1				1	1						1					1			1									
Low Rotor Speed (N1)	15														1	1	1			1		1	1							1	1	1												
LPC Stage Count	27												1		1	1	1			1	1	1	1		1					1	1	1	1											
LPC Airfoil Counts	18																1					1	1	1																				
Low Rotor Shaft Critical Speed	13																						1		1	1	1																	
LPC Axial Gapping	17																		1		1				1	1																		
LPC Length	24	1									1									1		1	1		1		1	1																
Weight	43																			1			1	1			1	1																
Production Cost	36																			1			1	1			1		1															
Engine Core Flow	3				1	1	1	1	1			1			1	1	1				1	1	1							1														
LPC Disk/Drum Design	22			1														1				1						1	1		1													
LPC Operability (Surge Margin)	25																1			1	1	1	1									1												
Overall Pressure Ratio	35																						1										1											
LPC Blade Tip Clearance	19																				1											1		1										
LPC Bleeds (Config. & Flows, Cust/TCA)	20																		1		1								1			1			1									
HPT Blade Tip Clearance	12																																		1	1								
Low Rotor Shaft Design	14																										1										1							
LPT BladeTip Clearance	28														1																							1						
LPT Case Cooling	29																																		1				1					
Maintenance Cost	32																			1			1	1			1													1				
Noise	34																									1															1			
T4 (Combustor Exit Temperature)	39																																		1							1		
Thermal Management Subsystems	40																																		1								1	
TSFC	42																																		1									1

Figure B-4
LPC Partitioned DSM

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47
Aircraft/Engine Range	1	1																																														
Bearing Locations and Compartments L/O	2		1																		1																											
HPC Blade Root Stress (Limiting)	3			1							1																													1								1
By-Pass Ratio	4				1																																											
Combustor Temperature	5					1				1										1																												
Durability/Coatings Selection	6						1																																									
Durability/Life	7							1					1																																			
Emissions	8								1																													1									
Engine Core Flow	9									1		1					1		1			1	1	1																			1					
High Rotor Speed (N2)	10										1	1							1			1																										
High-Low Spool Work Split	11									1		1					1		1			1	1	1								1																
HPC Axial Gapping	12												1						1																		1										
HPC Airfoil Counts	13										1			1									1	1																								
HPC Bleeds (Config. & Flows, Cust/TCA)	14						1								1				1			1	1													1	1											
HPC Case Design	15														1	1	1					1			1																							
HPC Diameter (Inlet/Exit)	16																1																															
HPC Disk/Drum Design	17										1							1													1			1		1											1	
HPC Efficiency	18											1			1				1			1	1		1																							1
HPC Exit Pres/Temp Profile	19																		1	1																			1									1
HPC Length	20												1			1					1			1							1																1	1
HPC Operability (Surge Margin)	21														1				1			1	1		1																							1
HPC Pressure Ratio	22	1			1							1					1		1			1	1	1											1					1			1					1
HPC Stage Count	23										1		1			1	1		1			1	1	1	1										1													1
HPC Tip Clearance	24															1			1						1													1									
HPT Efficiency	25																									1																						
HPT Expansion Ratio	26																										1																					
HPT Stage Count	27																											1																				
HPT Velocity Ratio	28																												1																			
Low Rotor Shaft Critical Speed	29																				1									1																		
Low Rotor Shaft Design	30																				1										1								1									
LPC Pressure Ratio (work)	31																														1																
Maintenance Cost	32						1									1								1									1													1		1
Material Selection	33																	1																1														1
Overall Pressure Ratio	34																																		1												
Production Cost	35															1							1	1												1										1		1
Reliability (Engine System)	36												1																							1									1		
Rotor Support System	37															1																					1									
T3 (HPC Exit Temperature)	38					1				1									1				1												1				1									1
T4 (Combustor Exit Temperature)	39														1																								1							
Thermal Efficiency	40																		1																					1							
Thermal Management Subsystems	41														1																										1						
Total Flow	42																																									1					
TSFC	43														1					1									1										1				1	1		1		
Turbine Cooling Air	44																									1	1												1						1			
Variable Geometry Configuration	45																					1	1																							1		
Weight	46																						1	1				1																		1	1	1
HPC Airfoil Des.(Aero/Stru,H/T,AR,t/b)	47										1		1	1					1			1	1											1														1

Figure B-5
HPC Unpartitioned DSM

		1	4	6	16	25	26	27	28	31	34	42	12	18	21	22	45	10	47	36	15	23	35	46	9	20	38	30	17	33	19	5	29	11	37	14	24	13	39	3	2	7	8	32	40	41	43	44
Aircraft/Engine Range	1 |1|																																														
By-Pass Ratio	4		1																																														
Durability/Coatings Selection	6			1																																													
HPC Diameter (Inlet/Exit)	16				1																																												
HPT Efficiency	25					1																																											
HPT Expansion Ratio	26						1																																										
HPT Stage Count	27							1																																									
HPT Velocity Ratio	28								1																																								
LPC Pressure Ratio (work)	31									1																																							
Overall Pressure Ratio	34										1																																						
Total Flow	42											1																																					
HPC Axial Gapping	12													1	1						1																													
HPC Efficiency	18														1	1	1			1														1		1	1											
HPC Operability (Surge Margin)	21														1	1	1			1																1	1											
HPC Pressure Ratio	22	1	1		1						1	1		1	1	1			1			1												1					1									
Variable Geometry Configuration	45															1	1	1																															
High Rotor Speed (N2)	10														1	1			1																1															
HPC Airfoil Des.(Aero/Stru,H/T,AR,t/b)	47												1	1	1	1		1	1											1									1										
Reliability (Engine System)	36												1				1			1																												
HPC Case Design	15				1										1						1																1	1										
HPC Stage Count	23				1						1		1	1	1	1		1	1		1	1															1										
Production Cost	35															1	1		1		1	1	1																									
Weight	46							1								1	1		1			1		1																									
Engine Core Flow	9				1							1		1	1	1						1			1									1															
HPC Length	20												1						1		1	1		1		1						1														
T3 (HPC Exit Temperature)	38										1			1		1			1						1		1					1																	
Low Rotor Shaft Design	30																									1	1	1																					
HPC Disk/Drum Design	17																	1					1	1				1	1	1																		
Material Selection	33																		1												1	1																		
HPC Exit Pres/Temp Profile	19														1					1										1				1																	
Combustor Temperature	5																								1						1	1																	
Low Rotor Shaft Critical Speed	29																									1							1															
High-Low Spool Work Split	11				1					1				1	1	1						1			1										1													
Rotor Support System	37																				1														1													
HPC Bleeds (Config. & Flows, Cust/TCA)	14			1												1	1	1				1			1													1											
HPC Tip Clearance	24														1							1													1		1											
HPC Airfoil Counts	13																	1		1				1															1									
T4 (Combustor Exit Temperature)	39																																					1			1										
HPC Blade Root Stress (Limiting)	3																			1	1																						1	1								
Bearing Locations and Compartments L/O	2																									1															1							
Durability/Life	7												1																													1						
Emissions	8																										1																1					
Maintenance Cost	32			1													1		1		1	1																						1				
Thermal Efficiency	40														1																														1			
Thermal Management Subsystems	41																																					1									1		
TSFC	43								1			1					1											1				1						1									1	
Turbine Cooling Air	44					1	1																				1																					1

Figure B-6
HPC Partitioned DSM

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
Bearing Locations and Compartments L/O	1	1																															
Bearing Technology (DN, Face Speed)	2		1																														
Bearings and Seals Design	3		1	1				1					1			1							1										
Combustor Pressure Loss	4				1				1	1	1															1			1		1		
Combustor Temperature	5					1			1	1					1							1											
Diffuser Delta Pressure Recovery	6						1	1				1										1											
Diffuser/Combustor Length	7	1					1	1		1	1	1																		1			
Durability/Coatings Selection	8				1	1			1												1		1										
Durability/Life	9									1																							
Emissions	10				1	1		1			1											1		1	1								
Engine Core Flow	11				1	1						1																					
High Rotor Speed (N2)	12												1																				
HPC Bleeds (Config. & Flows, Cust/TCA)	13													1																			
HPC Exit Pres/Temp Profile	14														1																		
HPC Pressure Ratio	15															1									1								
Low Rotor Shaft Critical Speed	16							1									1															1	
Low Rotor Shaft Design	17							1										1															
LPC Bleeds (Config. & Flows, Cust/TCA)	18																		1														
Maintenance Cost	19									1					1					1	1			1	1								
Material Selection	20																				1												
Overall Pressure Ratio	21																					1											
Production Cost	22								1												1		1		1		1		1				
T3 (HPC Exit Temperature)	23																					1		1									
T4 (Combustor Exit Temperature)	24											1		1					1			1			1			1	1				1
Thermal Management Subsystems	25																									1							
Total Flow	26																										1						
TSFC	27				1																				1			1					
Turbine Cooling Air	28																				1			1	1				1		1		
Weight	29						1	1		1						1					1				1					1			
Combustor Exit Temp Uniformity	30																														1		
Diffuser Structural Stiffness	31																															1	
Combustor Efficiency	32																																1

Figure B-7
Diffuser/Combustor Unpartitioned DSM

		1	2	9	12	13	14	18	20	21	25	26	30	31	32	23	4	5	6	7	8	10	11	15	22	24	27	28	29	3	16	17	19
Bearing Locations and Compartments L/O	1	1																															
Bearing Technology (DN, Face Speed)	2		1																														
Durability/Life	9			1																													
High Rotor Speed (N2)	12				1																												
HPC Bleeds (Config. & Flows, Cust/TCA)	13					1																											
HPC Exit Pres/Temp Profile	14						1																										
LPC Bleeds (Config. & Flows, Cust/TCA)	18							1																									
Material Selection	20								1																								
Overall Pressure Ratio	21									1																							
Thermal Management Subsystems	25										1																						
Total Flow	26											1																					
Combustor Exit Temp Uniformity	30												1																				
Diffuser Structural Stiffness	31													1																			
Combustor Efficiency	32														1																		
T3 (HPC Exit Temperature)	23									1						1																	
Combustor Pressure Loss	4			1							1		1				1				1	1						1					
Combustor Temperature	5			1			1			1								1			1												
Diffuser Delta Pressure Recovery	6									1									1	1			1										
Diffuser/Combustor Length	7	1		1															1	1		1	1						1				
Durability/Coatings Selection	8								1								1	1			1				1								
Emissions	10									1						1	1	1		1		1				1							
Engine Core Flow	11																1	1					1										
HPC Pressure Ratio	15																							1		1							
Production Cost	22								1			1									1				1	1		1					
T4 (Combustor Exit Temperature)	24					1		1		1					1								1			1	1	1					
TSFC	27																1									1	1						
Turbine Cooling Air	28								1				1			1										1		1					
Weight	29			1					1										1	1				1		1			1				
Bearings and Seals Design	3		1		1															1				1	1					1			
Low Rotor Shaft Critical Speed	16													1						1											1		
Low Rotor Shaft Design	17																			1												1	
Maintenance Cost	19			1			1		1							1										1							1

Figure B-8
Diffuser/Combustor Partitioned DSM

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43
Bearing Locations and Compartments L/C	1	1																																										
By-Pass Ratio	2		1																																										
Combustor Pressure Loss	3			1																																									
Development Cost	4				1																																								
Durability/Coatings Selection	5			1		1						1																					1										1		
Durability/Life	6						1							1																															
Emissions	7							1																													1							
Engine Core Flow	8								1								1	1																				1							
High Rotor Speed (N2)	9									1		1					1																												
HPC Bleeds (Config. & Flows, Cust/TCA)	10					1					1				1																													
HPT AN^2	11											1									1																							
HPT Airfoil Counts	12									1		1	1				1			1	1										1			1										1	
HPT Blade Tip Clearance	13											1		1		1																						1						1		
HPT Airfoil Design	14				1				1		1		1			1		1													1	1		1			1	1						
HPT Disk Design	15									1	1					1				1				1								1		1		1								1	
HPT Efficiency	16													1			1	1			1	1																				1		
HPT Expansion Ratio	17		1						1			1						1															1										1		
HPT Flow Parameter	18											1							1																									
HPT Length	19	1																		1	1		1		1										1								1	
HPT Stage Count	20									1		1						1			1																								
HPT Velocity Ratio	21											1	1					1				1																					
Low Rotor Shaft Critical Speed	22																			1			1																						
Low Rotor Shaft Design	23																			1				1																					
Low Rotor Shaft Torque	24																								1																				
Low Rotor Speed (N1)	25																									1																			
LPC Bleeds (Config. & Flows, Cust/TCA)	26																										1																		
LPC Disk/Drum Design	27																											1																1	
LPT Expansion Ratio	28		1																1										1				1									1		
LPT Velocity Ratio	29																		1											1															
Maintenance Cost	30												1		1						1										1	1						1							
Material Selection	31								1	1		1			1	1																1	1		1			1	1						1	
Overall Pressure Ratio	32																																1										
Production Cost	33								1			1	1		1	1				1	1												1		1				1							
Reliability (Engine System)	34					1	1					1		1	1																					1						1		
Rotor Support System	35													1										1													1								
T3 (HPC Exit Temperature)	36																																				1								
T4 (Combustor Exit Temperature)	37								1		1																1							1		1			1				1		
Thermal Efficiency	38																1																						1	1						
Thermal Management Subsystems	39										1																												1				
TSFC	40													1								1																1			1			
Turbine Cooling Air	41								1	1						1	1								1			1								1	1				1		
Weight	42												1							1	1																	1				1	
HPT Blade Root Stress (Limiting)	43								1			1			1	1																												1

Figure B-9
HPT Unpartitioned DSM

		1	2	3	4	24	25	26	32	36	11	18	9	17	8	20	19	37	41	22	23	28	42	35	31	5	10	15	13	16	12	14	30	33	21	6	34	43	7	27	29	38	39	40
Bearing Locations and Compartments L/O	1	1																																										
By-Pass Ratio	2		1																																									
Combustor Pressure Loss	3			1																																								
Development Cost	4				1																																							
Low Rotor Shaft Torque	24					1																																						
Low Rotor Speed (N1)	25						1																																					
LPC Bleeds (Config. & Flows, Cust/TCA)	26							1																																				
Overall Pressure Ratio	32								1																																			
T3 (HPC Exit Temperature)	36									1																																		
HPT AN^2	11										1					1																												
HPT Flow Parameter	18										1	1																																
High Rotor Speed (N2)	9										1		1																	1														
HPT Expansion Ratio	17		1						1		1			1	1				1																									
Engine Core Flow	8													1	1			1												1														
HPT Stage Count	20										1		1	1		1																												
HPT Length	19	1				1										1	1			1			1	1																				
T4 (Combustor Exit Temperature)	37							1	1						1			1	1								1										1							
Turbine Cooling Air	41						1			1			1	1	1			1	1			1								1														
Low Rotor Shaft Critical Speed	22																1			1																								
Low Rotor Shaft Design	23																1				1																							
LPT Expansion Ratio	28		1						1			1							1			1																						
Weight	42															1	1	1					1								1													
Rotor Support System	35																			1				1					1															
Material Selection	31									1	1		1		1			1					1		1			1				1	1	1											
Durability/Coatings Selection	5			1							1								1						1	1																		
HPC Bleeds (Config. & Flows, Cust/TCA)	10																									1	1					1												
HPT Disk Design	15												1				1				1		1	1	1		1	1						1										
HPT Blade Tip Clearance	13										1								1					1				1	1															
HPT Efficiency	16													1		1			1										1	1					1									
HPT Airfoil Counts	12										1		1			1	1						1							1	1		1	1										
HPT Airfoil Design	14				1					1	1				1			1							1		1			1		1	1	1										
Maintenance Cost	30															1		1							1						1	1	1											
Production Cost	33										1				1	1	1	1							1			1			1	1		1										
HPT Velocity Ratio	21										1			1																	1				1									
Durability/Life	6																															1				1								
Reliability (Engine System)	34										1								1							1			1			1				1	1							
HPT Blade Root Stress (Limiting)	43										1				1													1				1						1						
Emissions	7																	1																					1					
LPC Disk/Drum Design	27																						1																	1				
LPT Velocity Ratio	29											1																													1			
Thermal Efficiency	38																	1												1												1		
Thermal Management Subsystems	39																										1																1	
TSFC	40																	1											1						1									1

Figure B-10
HPT Partitioned DSM

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47
Bearing Locations and Compartments L/O	1	1															1	1								1																						
Bearing Reliability	2		1														1																															
Bearing Technology (DN, Face Speed)	3			1													1	1																														
By-Pass Ratio	4				1											1																																
Diffuser/Combustor Length	5					1													1																													
Engine Core Flow	6						1																					1																				
High Rotor Speed (N2)	7							1																																								
High-Low Spool Work Split	8								1																								1															
HPC Bleeds (Config. & Flows, Cust/TCA)	9									1																																						
HPC Disk/Drum Design	10										1							1																														
HPC Length	11											1					1		1																													
HPT Disk Design	12												1					1																														
HPT Flow Parameter	13													1																																		
HPT Length	14														1		1		1																													
Jet Velocity	15															1																																
Low Rotor Shaft Critical Speed	16	1				1						1			1		1	1		1	1			1								1	1			1												
Low Rotor Shaft Design	17	1				1						1			1		1	1	1	1												1				1			1			1						
Low Rotor Shaft Torque	18																		1	1																												
Low Rotor Speed (N1)	19								1											1						1				1																		
LPC Axial Gapping	20																1				1																											
LPC Bleeds (Config. & Flows, Cust/TCA)	21																					1																										
LPC Length	22																1						1																									
LPC Stage Count	23																1							1																								
LPT Airfoil Counts	24																			1					1								1															
LPT BladeTip Clearance	25																			1						1	1														1							
LPT Case Cooling	26									1												1					1			1																		
LPT Diameter (Inlet/Exit)	27						1																			1		1																				
LPT Disk Design	28																			1						1			1							1			1								1	
LPT Efficiency	29																									1	1			1	1		1	1														
LPT Expansion Ratio	30				1									1																	1							1								1		
LPT Length	31	1															1															1									1						1	
LPT Stage Count	32																1			1													1															
LPT Velocity Ratio	33													1						1								1					1	1														
Maintenance Cost	34																								1										1													
Material Selection	35																																			1												
Noise	36																								1							1					1											
Overall Pressure Ratio	37																																					1										
Production Cost	38																								1														1									
Propulsive Efficiency	39																																1							1								
Rotor Support System	40																1									1															1							
T3 (HPC Exit Temperature)	41																																									1						
Thermal Efficiency	42																													1													1					
Thrust	43																		1														1											1				
Total Flow	44																		1														1												1			
Turbine Cooling Air	45							1												1											1															1		
Weight	46																								1																						1	
LPT Airfoil Des.(Aero/Stru,H/T,AR,t/b)	47																																			1			1									1

Figure B-11
LPT Unpartitioned DSM

		7	9	13	15	21	35	37	41	4	30	45	18	5	32	6	11	14	24	8	38	46	19	26	29	33	27	25	1	16	17	20	23	31	40	28	47	2	3	10	12	22	34	36	39	42	43	44
High Rotor Speed (N2)	7	1																																														
HPC Bleeds (Config. & Flows, Cust/TCA)	9		1																																													
HPT Flow Parameter	13			1																																												
Jet Velocity	15				1																																											
LPC Bleeds (Config. & Flows, Cust/TCA)	21					1																																										
Material Selection	35						1																																									
Overall Pressure Ratio	37							1																																								
T3 (HPC Exit Temperature)	41								1																																							
By-Pass Ratio	4				1					1																																						
LPT Expansion Ratio	30			1				1		1	1	1																																				
Turbine Cooling Air	45	1									1	1											1																									
Low Rotor Shaft Torque	18										1		1										1																									
Diffuser/Combustor Length	5												1	1																																		
LPT Stage Count	32														1								1							1																		
Engine Core Flow	6															1											1																					
HPC Length	11												1				1													1																		
HPT Length	14												1					1												1																		
LPT Airfoil Counts	24														1				1				1																									
High-Low Spool Work Split	8							1		1					1	1				1																												
Production Cost	38																		1		1																											
Weight	46																		1			1																										
Low Rotor Speed (N1)	19																			1			1		1			1																				
LPT Case Cooling	26		1			1																		1	1																							
LPT Efficiency	29										1				1									1	1	1		1																				
LPT Velocity Ratio	33			1											1								1			1	1																					
LPT Diameter (Inlet/Exit)	27															1											1	1																				
LPT BladeTip Clearance	25																						1	1				1							1													
Bearing Locations and Compartments L/O	1																											1	1	1	1																	
Low Rotor Shaft Critical Speed	16						1							1	1		1	1					1						1	1	1	1	1	1														
Low Rotor Shaft Design	17						1		1				1	1			1	1			1		1						1	1	1			1														
LPC Axial Gapping	20																													1		1																
LPC Stage Count	23																													1			1															
LPT Length	31																					1							1	1				1	1													
Rotor Support System	40																											1		1					1													
LPT Disk Design	28						1														1	1	1					1								1												
LPT Airfoil Des.(Aero/Stru,H/T,AR,t/b)	47						1														1																1											
Bearing Reliability	2																													1								1										
Bearing Technology (DN, Face Speed)	3																													1	1								1									
HPC Disk/Drum Design	10																														1									1								
HPT Disk Design	12																														1										1							
LPC Length	22																																									1						
Maintenance Cost	34																		1																								1					
Noise	36																		1															1										1				
Propulsive Efficiency	39														1																														1			
Thermal Efficiency	42																								1																					1		
Thrust	43												1		1																																1	
Total Flow	44												1		1																																	1

Figure B-12
LPT Partitioned DSM

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Bearing Locations and Compartments L/O	1	1							1					1	1			1				1
Bearing Reliability	2		1	1				1						1							1	
Bearing Technology (DN)	3		1	1	1			1						1	1	1						
Seals Design	4			1	1		1	1								1				1		
Development Cost	5					1																1
Diffuser/Combustor Length	6	1					1															1
High Rotor Speed (N2)	7			1	1			1														1
HPC Case Design	8								1													
HPC Length	9	1								1												1
HPC Tip Clearance	10										1											1
HPT Blade Tip Clearance	11											1										
HPT Length	12	1											1									1
Low Rotor Shaft Critical Speed	13	1		1										1								
Low Rotor Shaft Design	14	1		1											1							
Low Rotor Speed (N1)	15		1	1	1											1						1
LPC Length	16	1															1					1
LPT BladeTip Clearance	17																	1				1
LPT Length	18	1																	1			1
Material Selection	19																			1		
Oil & Lube System	20	1	1																		1	
Rotor Support System	21								1			1		1				1				1

Figure B-13
Mechanical Components Unpartitioned DSM

		8	11	19	13	17	21	1	6	7	2	3	4	14	15	20	5	9	10	12	16	18
HPC Case Design	8	1																				
HPT Blade Tip Clearance	11		1																			
Material Selection	19			1																		
Low Rotor Shaft Critical Speed	13				1			1				1										
LPT BladeTip Clearance	17					1	1															
Rotor Support System	21	1	1		1	1	1	1														
Bearing Locations and Compartments L/O	1	1			1	1	1	1						1								
Diffuser/Combustor Length	6						1	1	1													
High Rotor Speed (N2)	7						1			1		1	1									
Bearing Reliability	2				1					1	1	1				1						
Bearing Technology (DN)	3				1					1	1	1	1	1	1							
Seals Design	4			1					1	1		1	1		1							
Low Rotor Shaft Design	14							1				1		1								
Low Rotor Speed (N1)	15						1				1	1	1		1							
Oil & Lube System	20							1			1					1						
Development Cost	5						1										1					
HPC Length	9						1	1										1				
HPC Tip Clearance	10						1												1			
HPT Length	12						1	1												1		
LPC Length	16						1	1													1	
LPT Length	18						1	1														1

Figure B-14
Mechanical Components Partitioned DSM

Appendix C

P&W Systems Engineering Process flow charts.

Figure C-1

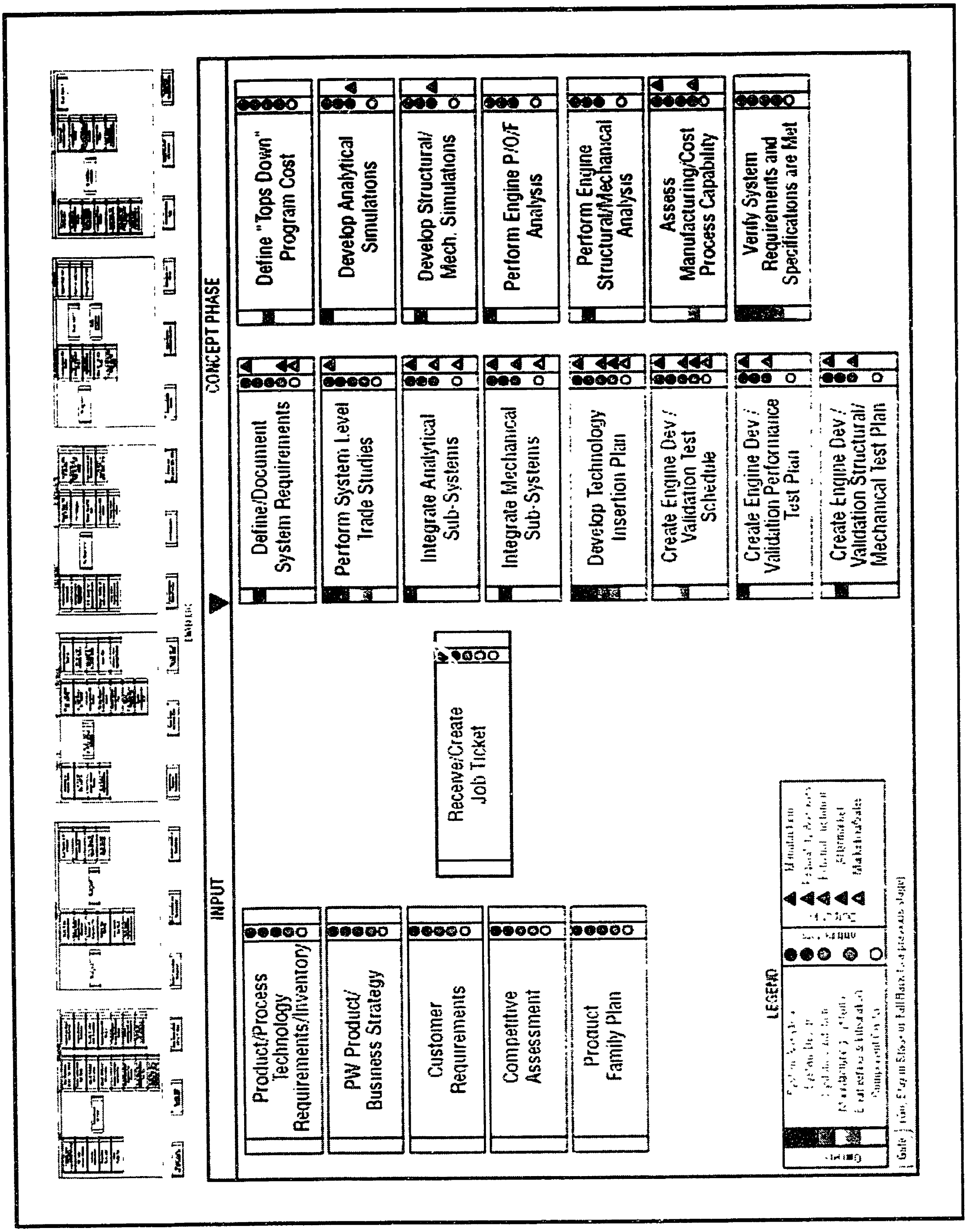

INPUT
Product/Process Technology Requirements/Inventory
PW Product/ Business Strategy
Customer Requirements
Competitive Assessment
Product Family Plan
Receive/Create Job Ticket
CONCEPT PHASE
Define/Document System Requirements
Perform System Level Trade Studies
Integrate Analytical Sub-Systems
Integrate Mechanical Sub-Systems
Develop Technology Insertion Plan
Create Engine Dev / Validation Test Schedule
Create Engine Dev / Validation Performance Test Plan
Create Engine Dev / Validation Structural/ Mechanical Test Plan
Define "Tops Down" Program Cost
Develop Analytical Simulations
Develop Structural/ Mech. Simulations
Perform Engine P/O/F Analysis
Perform Engine Structural/Mechanical Analysis
Assess Manufacturing/Cost Process Capability
Verify System Requirements and Specifications are Met
LEGEND

Figure C-2

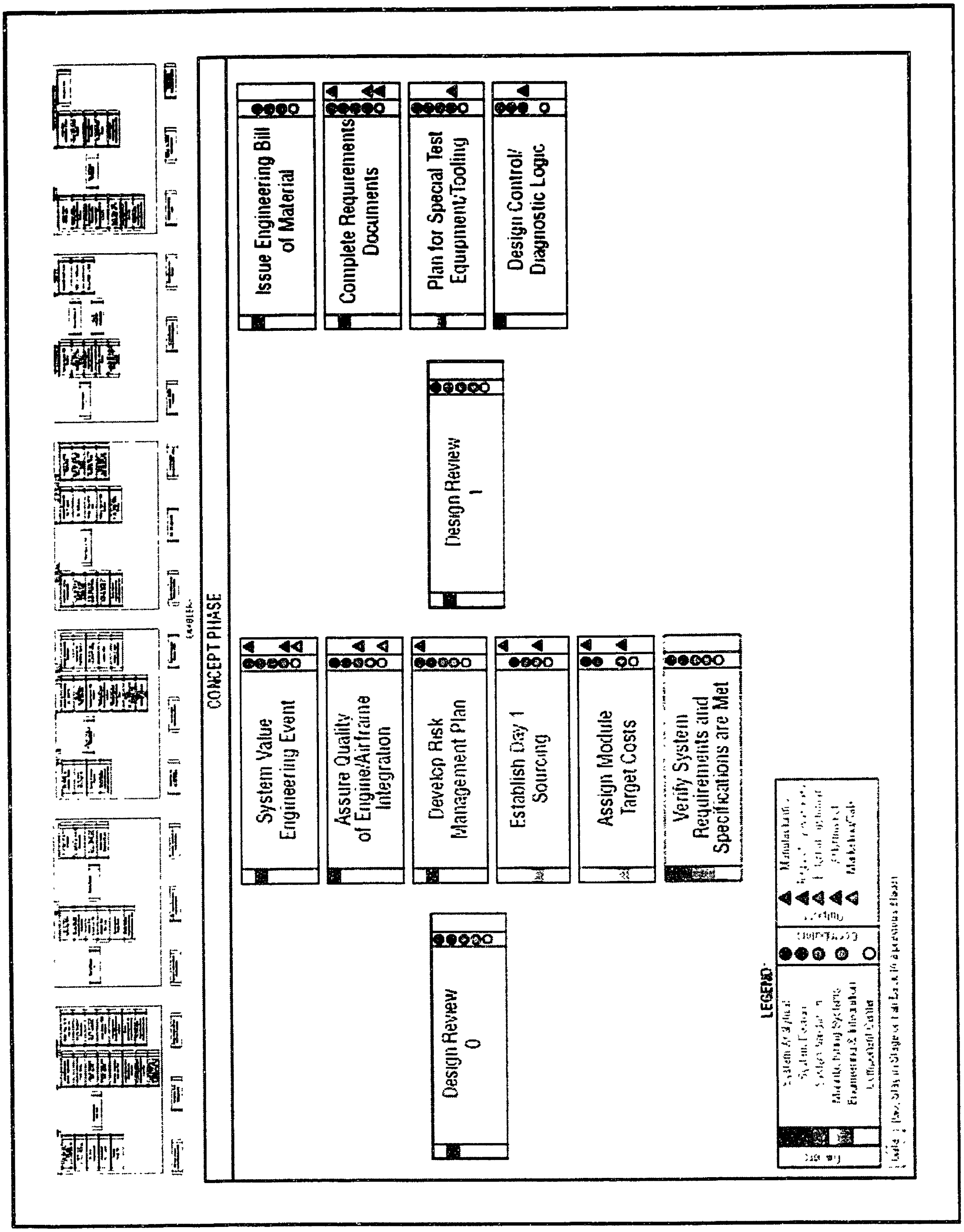

CONCEPT PHASE
Issue Engineering Bill of Material
Complete Requirements Documents
Plan for Special Test Equipment/Tooling
Design Control/ Diagnostic Logic
Design Review 1
System Value Engineering Event
Assure Quality of Engine/Airframe Integration
Develop Risk Management Plan
Establish Day 1 Sourcing
Assign Module Target Costs
Verify System Requirements and Specifications are Met
Design Review 0
LEGEND

Figure C-3

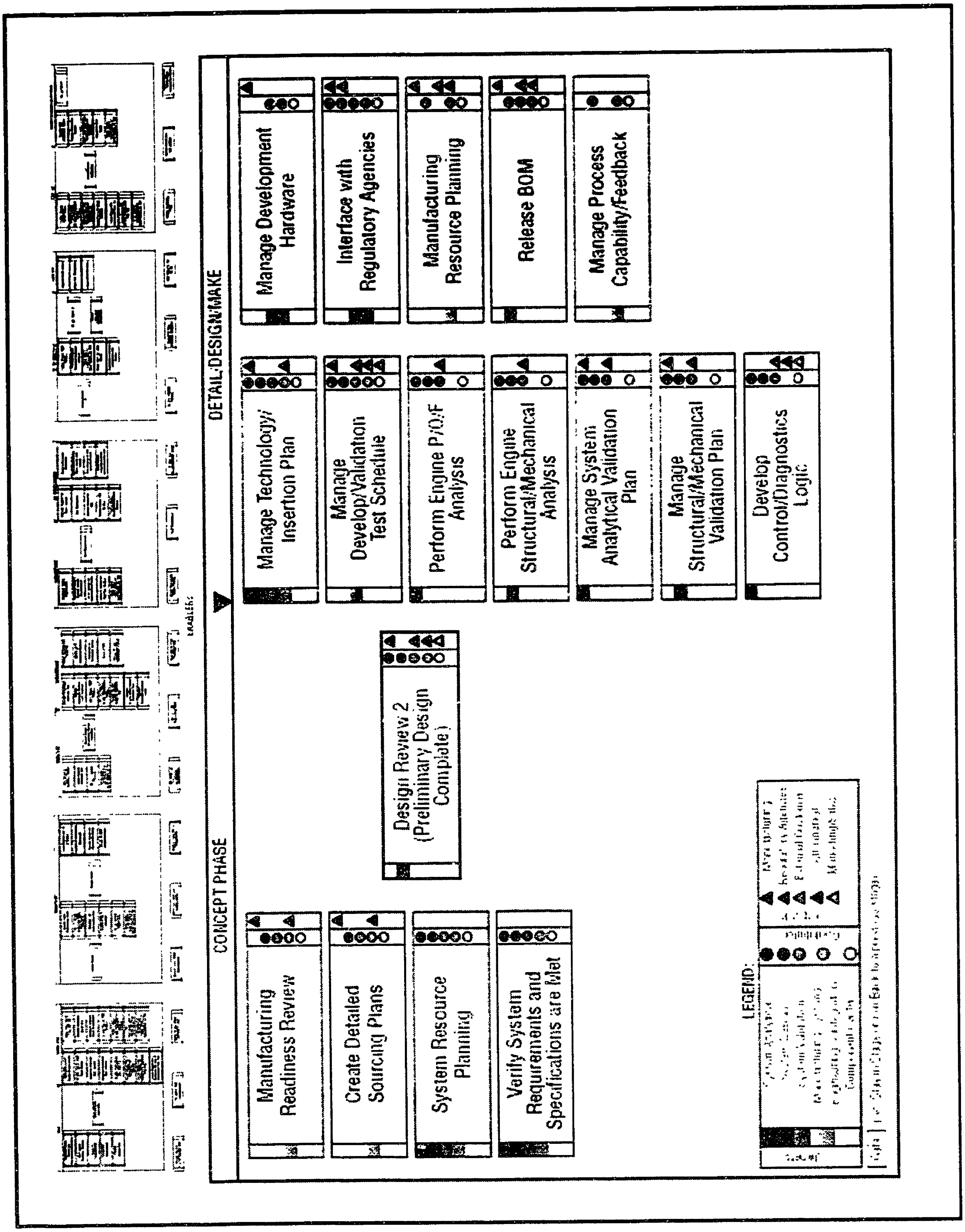

CONCEPT PHASE
DETAIL DESIGN/MAKE
Manufacturing Readiness Review
Create Detailed Sourcing Plans
System Resource Planning
Verify System Requirements and Specifications are Met
Design Review 2 (Preliminary Design Complete)
Manage Technology/Insertion Plan
Manage Develop/Validation Test Schedule
Perform Engine P/Q:F Analysis
Perform Engine Structural/Mechanical Analysis
Manage System Analytical Validation Plan
Manage Structural/Mechanical Validation Plan
Develop Control/Diagnostics Logic
Manage Development Hardware
Interface with Regulatory Agencies
Manufacturing Resource Planning
Release BOM
Manage Process Capability/Feedback
LEGEND:

Figure C-4

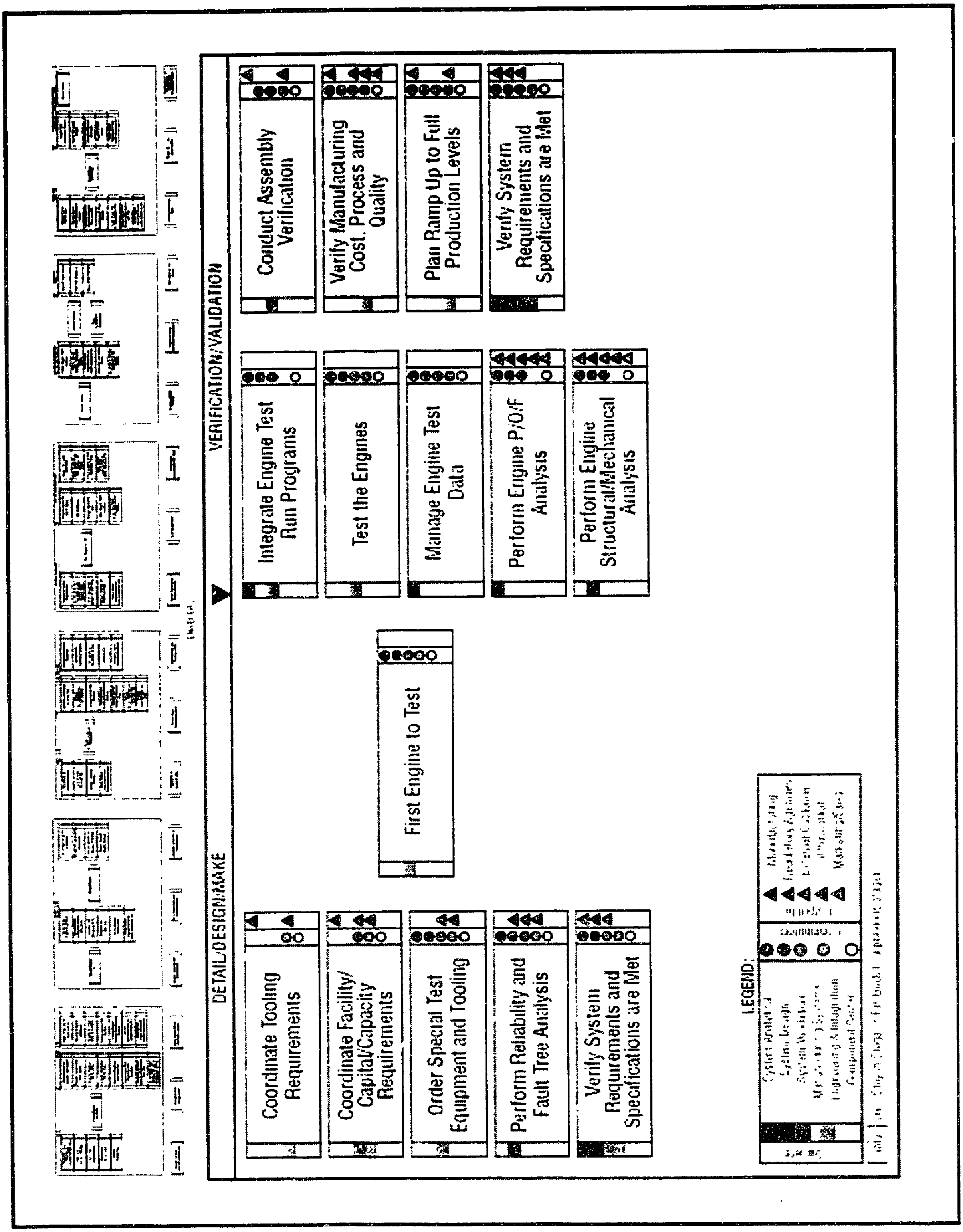

DETAIL DESIGN/MAKE
VERIFICATION/VALIDATION
Coordinate Tooling Requirements
Coordinate Facility/Capital/Capacity Requirements
Order Special Test Equipment and Tooling
Perform Reliability and Fault Tree Analysis
Verify System Requirements and Specifications are Met
First Engine to Test
Integrate Engine Test Run Programs
Test the Engines
Manage Engine Test Data
Perform Engine P/O/F Analysis
Perform Engine Structural/Mechanical Analysis
Conduct Assembly Verification
Verify Manufacturing Cost, Process and Quality
Plan Ramp Up to Full Production Levels
Verify System Requirements and Specifications are Met
LEGEND:

Figure C-5

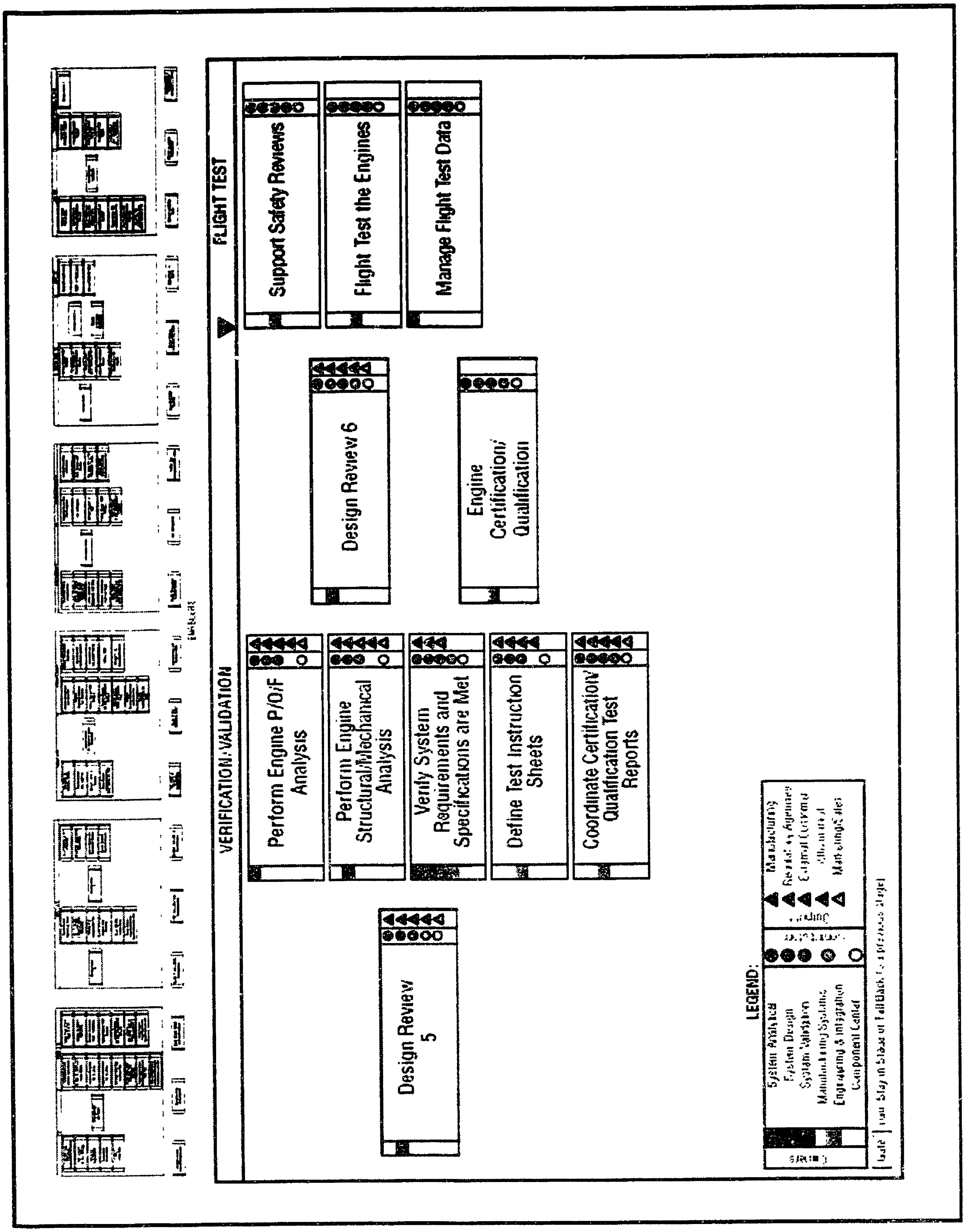

VERIFICATION/VALIDATION
FLIGHT TEST
Support Safety Reviews
Flight Test the Engines
Manage Flight Test Data
Design Review 6
Engine Certification/ Qualification
Perform Engine P/O/F Analysis
Perform Engine Structural/Mechanical Analysis
Verify System Requirements and Specifications are Met
Define Test Instruction Sheets
Coordinate Certification/ Qualification Test Reports
Design Review 5
LEGEND:
System Design
Component Center
Manufacturing

Figure C-6

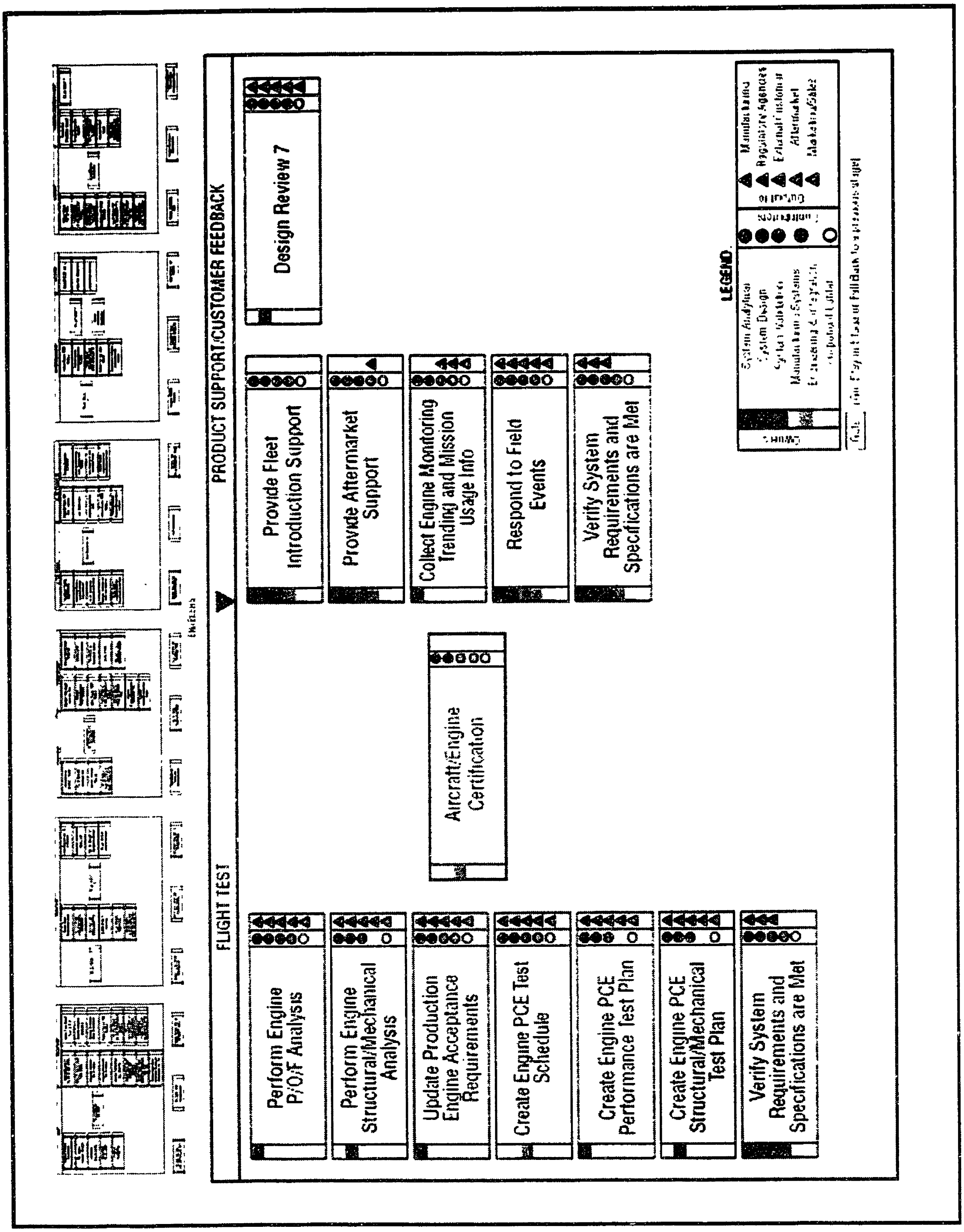
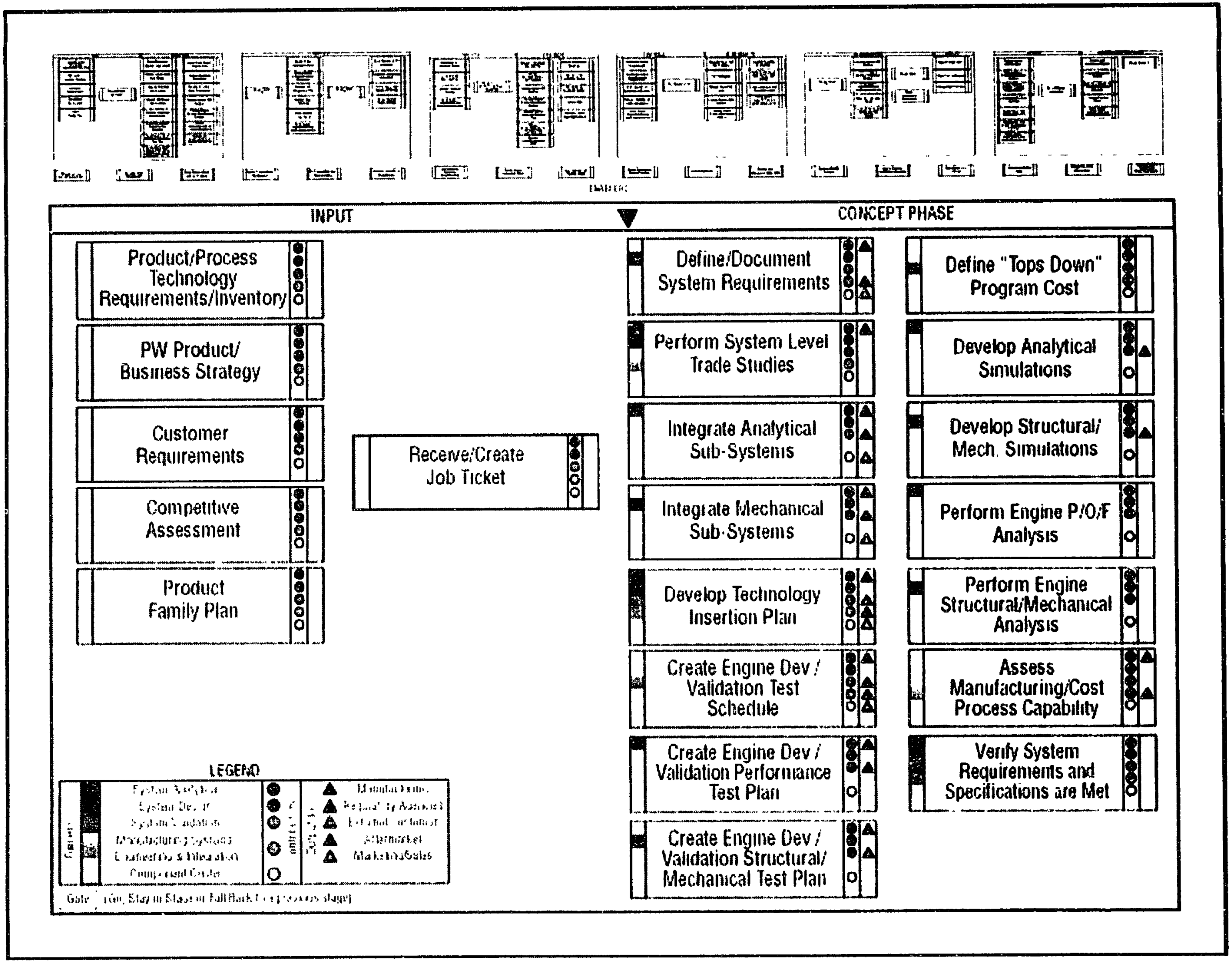

FLIGHT TEST
PRODUCT SUPPORT/CUSTOMER FEEDBACK
Perform Engine P/Q/F Analysis
Perform Engine Structural/Mechanical Analysis
Update Production Engine Acceptance Requirements
Create Engine PCE Test Schedule
Create Engine PCE Performance Test Plan
Create Engine PCE Structural/Mechanical Test Plan
Verify System Requirements and Specifications are Met
Aircraft/Engine Certification
Provide Fleet Introduction Support
Provide Aftermarket Support
Collect Engine Monitoring Trending and Mission Usage Info
Respond to Field Events
Verify System Requirements and Specifications are Met
Design Review 7
LEGEND
System Analysis
System Design
System Validation
Manufacturing Systems
Manufacturing
Regulatory Agencies
External Customer
Aftermarket
Marketing/Sales

Figure C-7


INPUT
CONCEPT PHASE
Product/Process Technology Requirements/Inventory
PW Product/ Business Strategy
Customer Requirements
Competitive Assessment
Product Family Plan
Receive/Create Job Ticket
Define/Document System Requirements
Perform System Level Trade Studies
Integrate Analytical Sub-Systems
Integrate Mechanical Sub-Systems
Develop Technology Insertion Plan
Create Engine Dev / Validation Test Schedule
Create Engine Dev / Validation Performance Test Plan
Create Engine Dev / Validation Structural/ Mechanical Test Plan
Define "Tops Down" Program Cost
Develop Analytical Simulations
Develop Structural/ Mech. Simulations
Perform Engine P/O/F Analysis
Perform Engine Structural/Mechanical Analysis
Assess Manufacturing/Cost Process Capability
Verify System Requirements and Specifications are Met
LEGEND
System Analysis
System Design
System Validation
Manufacturing Systems
Engineering & Integration
Component Center
Manufacturing
Repair & Assembly
External Partners
Aftermarket
Marketing/Sales
Gate (Go, Stay in Stage or Fall Back to previous stage)

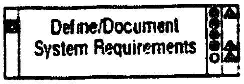
Appendix D

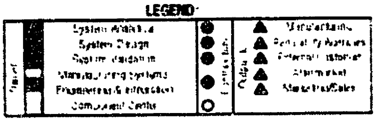
Examples of web pages from the P&W Systems Engineering Process

Figure D-1

Pratt & Whitney Home Page| System Engineering Overall Chart

Define/Document System Requirements





Description:

Systems requirements are defined by using the customer's specification or other applicable document in conjunction with P&W's strategic product and technology plans. They also include applicable government/regulatory requirements combined into the "Propulsion System/Component Requirements" document. The document is signed and issued at program launch and can be modified by an appropriate process thereafter. The document is divided into four sections: Systems, components, major parts, and resources.

PHASES	**(That the Task Resides In)**
	Input
X	Concept Phase
	Detail/Design/Make
	Verification/Validation
	Flight Test
	Product Support/Customer Feedback
	Enablers

OWNERS		**CONTRIBUTORS**
	System Analytical	X
X	System Design	X
	System Validation	X
	Manufacturing Systems, Engineering and Integration	X
	Component Center	X

OUTPUT TO	
Manufacturing	X
Regulatory Agencies	
External Customer	
Aftermarket	X
Marketing / Sales	X

Figure D-1 (cont.)

Process Deliverables:

The "Propulsion System/Components Requirements" document

Related Documentation:

Customer specification@ENTER LINK

Previous model design criteria@ ENTER LINK

Internal technical documents@ENTER LINK??

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Any questions/comments, please contact Cindy McComb-Gavello(mccombcl@pweh.com)

Date of Birth: March 3, 1998

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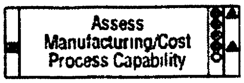
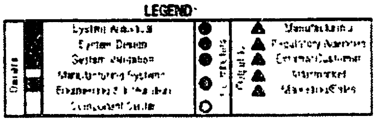
Figure D-2

Pratt & Whitney Home Page| System Engineering Overall Chart

Assess Manufacturing/Cost Process Capability





Description:

Designing to manufacturing "process capability" is key to meeting the goals of low cost, high quality, on-time delivery of our product. While assessing Manufacturing Process Capability, the analyst must consider a) whether the proposed technology or process currently exists within P&W or our approved supplier base; and b) what kind of tolerances can be held consistently for the features and feature characteristics that will be produced by the proposed process. If process capability does not exists due to lack of technology or other reasons, an assessment of product requirements versus technology development must be completed to determine whether the proposed process will be pursued.

PHASES	(That the Task Resides In)
	Input
X	Concept Phase
	Detail/Design/Make
	Verification/Validation
	Flight Test
	Product Support/Customer Feedback
	Enablers

OWNERS		CONTRIBUTORS
	System Analytical	X
	System Design	X
	System Validation	X
X	Manufacturing Systems, Engineering and Integration	X
	Component Center	X

	OUTPUT TO	
	Manufacturing	X
	Regulatory Agencies	
	External Customer	
	Aftermarket	X
	Marketing / Sales	

Figure D-2 (cont.)

Process Deliverables: What are the outputs of this task ?

Hardware design that falls within current or expected manufacturing process capabilities. Design meets all technical, performance, and manufacturing requirements (stress, weight, cost, quality, etc.). This is an on going task starting from conceptualization phase and carrying though production run. Process capability data will be collected on an on-going and continuous basis to define manufacturing process capability for all product centers, business units, cells, machines. Process capability to be defined for features (slots, bosses, flanges, etc.) and characteristics of those features (profile, true position, etc.)

Related Documentation: What and where are the related documentation / procedures for this task ?

Product Center Process Capability Catalogue

Technology & Production Readiness (T&PR) Best Practices Home Page

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Any questions/comments, please contact Cindy McComb-Gavello(mccombcl@pweh.com)

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