

**Systems Development Technical Interactions and Innovation:  
A Networks-Based Investigation**

By Pedzisayi O. Makumbe

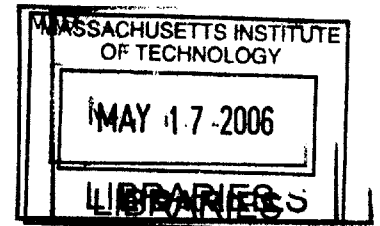
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Submitted to the Engineering Systems Division  
In Partial Fulfillment of the Requirements for the Degree of

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Signature of Author: \_\_\_\_\_

\_\_\_\_\_  
MIT Engineering Systems Division  
June 2006

Certified by: \_\_\_\_\_

\_\_\_\_\_  
James M. Utterback  
Professor of Management and Innovation, and Engineering Systems  
Thesis Supervisor

Certified by: \_\_\_\_\_

\_\_\_\_\_  
Kirkor Bozdogan  
Architectural Associate, CTPID  
Thesis Supervisor

Accepted by: \_\_\_\_\_

\_\_\_\_\_  
Richard de Neufville  
Professor of Civil and Environmental Engineering, and Engineering Systems  
Chair, Engineering Systems Division Education Committee

**BARKER**

For my parents, Kate and Claud Makumbe

Sango Rinopa Waneta<sup>1</sup>  
*-Shona Proverb*

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<sup>1</sup> Weeping may last the night, but joy comes in the morning

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## **Abstract**

The development of complex engineering systems such as aircraft engines involves many cross functional teams that are usually geographically distributed. These teams interact in several ways but one of the most important set of interactions during the product development phase is the flow of technical information which is largely used for coordination and problem solving. For analytical purposes, these technical information flows can be represented as a directed network. This thesis develops a context and a research design that can help one investigate the impact of the resultant network structure on innovation in complex engineering systems.

The broad context can be divided into two: theoretical and real world contexts. The theoretical context is developed by reviewing literature at the intersection of networks and innovation, and the real world context is typified by a modular enterprise developing a complex engineering system. Within this broad context, the research area of interest is framed by a set of hypotheses that lead to precise innovation measures and characterizations.

The research design is motivated by the context and intended theoretical contributions. It consists of two major sections. The first section discusses and critiques methodologies for constructing networks and proposes a methodology more suited to this engineering systems development context. The second section describes a two-stage model whose variables include network structural properties such as structural holes, nodal degree, tie strength, and innovation output. It also describes a methodology for investigating the relationship between network density and the innovation development subprocess.

Finally, the context and research design are tied together to create an instantiation of the measurement and characterization of innovation in complex engineering systems development. The characterization considers product innovation as radical, architectural, modular or incremental, and process innovation as organizational / coordination-based or technical. The measures of innovation include granted patents, implemented employee suggestions, product literature based innovation counts and results from structured interviews with the two leaders from each node in the network.

**Thesis Supervisors:** James Utterback, Professor of Management and Innovation, and Engineering Systems; and Kirk Bozdogan, Principal Research Associate, CTPID

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# Chapter 1: Introduction

## **Introduction**

How does one characterize or measure innovation in a complex engineering system? The answer depends on the specific research context, research design as constrained by resources and researcher's intended theoretical contributions. This thesis uses an example of an aircraft engine's network of product development cross functional teams to specify a research context and a research design that lead to a precise instantiation of the answer to the question above.

The thesis is structured around the illustrative example. The rest of this opening chapter introduces complex engineering systems and the focus of the thesis. Though engineering systems have several substages in their lifecycle, I will focus on the development phase. Additionally, I will posit an illustrative research question on complex engineering systems (viewed from a network perspective) and innovation in an attempt to be precise in the rest of the thesis.

Chapter 2 builds on the research question, and describes innovation and the various innovation subprocesses. The chapter begins with a generic, widely quoted definition of innovation, and ends with more specific definitions of innovation as applied to the development of engineering systems and innovation.

Chapter 3 builds on the context of the illustrative research question and innovation definitions, and reviews the use of Design Structure Matrices in product development. Towards the end of the chapter, I will propose network analysis as a tool that can help researchers improve research in systems development and innovation. This is because network analysis enables researchers to quantify and increase precision in their work. Additionally, network analysis has not been extensively applied in the context of systems development; thus there is an opportunity for making an academic contribution.

Chapter 4 brings together the networked systems development context (chapter 3) and innovation (chapter 2) more explicitly. In the chapter I will review literature on networks and innovation with an emphasis on how the network structure affects innovation, and pose hypotheses meant to partially fill the gap in the literature. The literature mainly comes from the interorganizational networks, R&D communication networks and social networks knowledge domains because literature particular to networks and systems development at the team level is limited. Borrowing from these knowledge domains makes sense because some mechanisms behind innovation in the three domains apply to the networked product development context as well.

The literature review reveals that most networks literature simply treats innovation as an output. It neither considers the different types of innovation nor does it consider innovation as a process. As a result, I will develop a set of five hypotheses that takes into account the different types of innovation as well as the different stages of the innovation process.

Chapter 5 reviews research methods that have been used by other researchers in similar contexts, and at the end of the chapter I propose a research design suitable for the illustrative research question. The research design is focused on constructing the network of technical interactions and measuring the different types of innovation discussed in chapter 2.

### **Complex engineering systems**

Most of today's technological artifacts exist as components of complex engineering systems, which are defined as "systems that depend on technology or technological artifacts for their existence" (Hastings, 2004; p. 1). Examples of these complex engineering systems range from the Global Positioning Systems, the Massachusetts Central Artery Tunnel to complex product systems such as aircrafts, satellites and jet engines. By their nature, engineering systems are very large, complex and embedded in human lives to the extent that they have *highly coupled* social, human, political as well as technical components on which they depend for their functionality. Where these components intersect, the enterprise emerges as a form of mediating the interfaces

between the various components (Allen, Nightingale, & Murman, 2004). In other words, the enterprise serves as a coordinating system surrounding the complex engineering systems (Baldwin & Clark, 2000).

Since all engineering systems have a development phase as part of their lifecycle (Crawley & Weigel, 2004), I am going to focus on the complex engineering system development enterprise (i.e. the product development organization<sup>2</sup>.) The importance of the development organization cannot be overemphasized. “Product development affects customer choice (through new products) and manufacturing, with consequent effects on productivity, quality and market share” (Clark, Chew, & Fujimoto, 1987; p. 730) Moreover, complex product designs endure for a long time. Thus each design has an enduring impact on the organization through engineering know-how, information systems and procedures, which can outlive the impact of the design in the market (Clark et al., 1987). Wheelwright and Clark (1992) added that “ the development of new products and processes increasingly is a focal point of competition. Firms that get to the market faster and more efficiently with products that are well matched to the needs and expectations of target customers create significant competitive leverage” (p. 1) As an example of the significance of the development phase in engineering systems, Whitney (1988) mentioned that 70% of the cost of manufacturing truck transmissions at GM, and 80% of the cost of producing each of some 2000 components at Rolls Royce is determined during the design phase.

In the development enterprise, I am going to focus on technical interactions i.e. technical information flows largely used for coordination and problem solving (Allen, 1997; Hauptman, 1996; Sosa, Eppinger, Pich, McKendrick, & Stout, 2002). Addressing the development enterprise technical interactions helps us to address structural complexity in the complex engineering system. Efficiently addressing this structural complexity – defined as the numerousness of components whose interconnection, interaction or

---

<sup>2</sup> I am going to use the two terms interchangeably though “complex engineering system development enterprise” expresses my ideas better. It indicates my focus on complex product systems (i.e. not coffee machines), while the “enterprise” refers to the size of the development organization which can reach thousands of engineers in different countries and companies. However, the term “product development organization” fits much more seamlessly with the literature.

interdependence is difficult to understand (Moses, 2004) - helps us to design, produce and manage the complex engineering systems better. In a nutshell, an enterprise that efficiently addresses the structural complexity improves the economics of the engineering system (Baldwin et al., 2000).

### **Illustrative research context and question**

#### Context

In order to avoid a grandiose discussion of development interactions, I am going to ground this work on an aircraft engine as an example of a complex engineering system. More specifically, I will focus on the PW4098 engine<sup>3</sup>. By using the relatively modular<sup>4</sup> aircraft engine as an example, I have also limited the discussion to modular design organizations (Sanchez & Mahoney, 1996). This restriction is not far fetched given that many other engineering systems are designed in modular design organizations. For instance, Mercedes-Benz SUVs produced in Alabama and Volkswagen trucks produced in Brazil are designed in modular design organizations (Baldwin & Clark, 1997).

The traditional hierarchical view of a company which is part of a development enterprise is shown in Figure 1 below. Each hierarchical level is labeled and an example provided in the diagram. An aircraft engine is rarely developed by one organization in its entirety, hence this same hierarchical structure would be repeated with some minor variations for key suppliers (suppliers that *design and develop* engine components) and partners in the development program. Figure 2 provides a different view of the design organization, and this network view is the preoccupation of this research. The network view is particularly useful as we move “away from the individualist, essentialist and atomistic explanations toward more relational, contextual and systemic understandings” (Borgatti & Foster, 2003; p. 991) in engineering systems.

Each node in the network is a cross functional product development team, which is known by different names depending on the company. For example, the cross functional

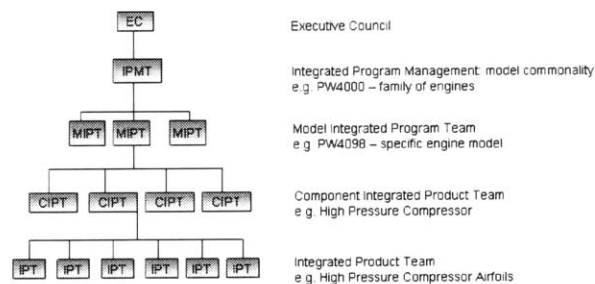
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<sup>3</sup> See Appendix A for information on the PW4000-112” engine series

<sup>4</sup> There is no absolute scale of modularity, hence some authors could argue that an aircraft engine is highly integrated. However, P&W development is modular based on Sanchez and Mahoney’s definition.

team is known as an Integrated Product Team (IPT) at Pratt and Whitney, and as a Product Development Team (PDT) at GM. Sticking to the Pratt and Whitney example, I am going to use IPT to denote a cross functional team in the rest of this thesis. Each IPT is responsible for designing, developing and validating detailed parts of the engine, and the IPT is composed of technically diverse engineers from design, systems, supplier management, customer support, repair support and manufacturing (Glynn & Pelland, 2000; p. 32). The exact responsibilities of IPTs at partner or supplier organizations generally vary depending on the organization structure of the partner/supplier organization and the arrangement between the lead contractor and the supplier/partner.

Some IPTs are part of the lead contractor while others are not. For instance, in designing and developing the PW6000, MTU of Germany had several IPTs responsible for designing and developing the low-pressure turbine and high pressure compressor. Other IPTs belong to partner organization e.g. the V2500 has IPTs at Pratt and Whitney, Rolls Royce, Japanese Aero Engines Cooperation, and MTU Aero Engines. Within Pratt and Whitney itself, the organization structure is loosely coupled (Sanchez et al., 1996) because the IPTs are geographically dispersed. Some IPTs are located in Middletown, East Hartford and North Haven in Connecticut, while others are located in New Brunswick, Maine.



**Figure 1: Traditional view of a P&W design organization from Glynn et al. (2000)**

**Figure 2: Design and development enterprise: networked view**

However, the number of suppliers can be very large, hence I am going to draw the boundary of the networked design enterprise by limiting the IPTs included in the network to IPTs that designed and developed engine components. Each link between the IPTs represents a horizontal (vs. vertical (Monteverde & Teece, 1982)) flow of technical information during the system development process.

### Question

As I mentioned above, I am interested in the network view of the development enterprise. Networks can be viewed from connectionist and/or structuralist points of view. The connectionist view is predominantly concerned with the flow of resources or information along the “pipes” linking the different nodes while the structuralist view is concerned with the topological configuration of the network ties and nodes (Coulon, 2005). From these two views, I am most interested in the structuralist view. However, some researchers argue that the two views are interlinked and should not be separated (Rowley, Behrens, & Krackhardt, 2000); hence I will borrow from the connectionist view where it helps our understanding of interactions during the product development phase and their relationship with innovation.

While research on IPTs and their interactions has been extensive (see <http://www.dsmweb.org/publications.htm> or Chapter 3 for a summary of the DSM literature), my illustrative research question comes from the fact that current research on interactions among IPTs has not investigated the impact of the network structure on innovation. I intend to take the IPT network structure a little further by analyzing the impact of the network structure on innovation produced by the IPTs. By innovation, I mean when *new* solutions are developed to close the gap between current performance and requirements. This idea of using the network as an independent variable has been a growing tradition in interorganizational network research since the mid 1990s.

As mentioned above, the network approach brings a deeper understanding of innovation in a relational, systemic context. The importance of innovation in a systemic context is exemplified by Thomas Edison’s work. Not only did he focus his efforts on inventing the

electric bulb, he also focused on “the larger *system* of electric lighting” (Utterback, 1994; pp. 61).

In a nutshell, my illustrative research intentions are to investigate whether and how the IPT network structure influences innovation developed into an engineering system (product innovation) or during the development of the engineering system (process innovation).

## Chapter 2: Definition and Classification of Innovation

### **Introduction**

In this chapter, I will define and characterize both product and process innovation as the terms apply to this research. The definitions and the characterizations of both types of innovation are grounded in the context of complex engineering systems development. Though innovation is largely treated as an output in the networks literature, innovation is a process as well. As a result, I will separately describe the product innovation process and the process innovation process, with an emphasis on innovation stages or subprocesses that I intend to use in the forthcoming chapters.

Structurally, the chapter starts with a generic definition of innovation. From the generic definition, I narrow down onto a definition more applicable to the product development context, and then describe four types of product innovation whose characterization is particularly useful in a systems context. The product innovation section of the chapter ends with an explanation of the different subprocesses involved in the product innovation process, and the concept of innovation hierarchy. Similarly, the process innovation section starts by defining process innovation and moves on to the process of process innovation. The chapter ends with a summary of the key definitions.

### **Definition of innovation**

Perhaps the most widely quoted and most comprehensive definition of innovation is Schumpeter's (1934) definition. He defined innovation as:

- The commercial or industrial application of something new...
- A new product or process or method of production...
- A new market or source of supply...
- A new form of commercial business or financial organization...
- A new combination is created... (p. 66)

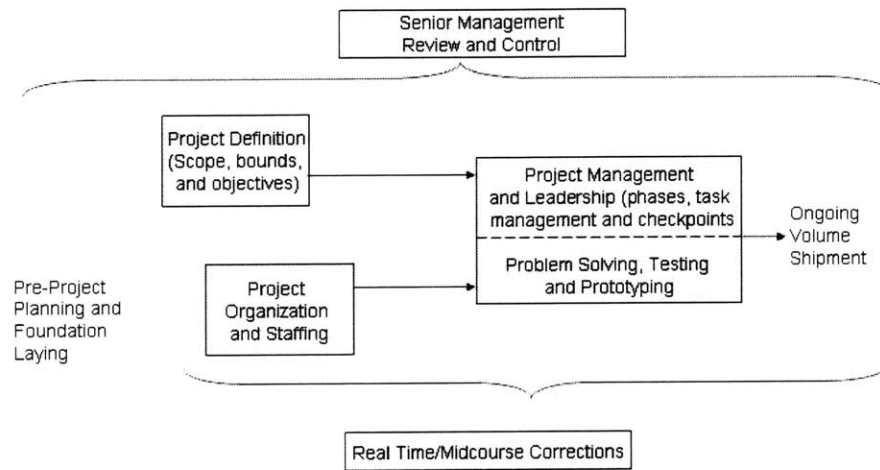
Various conceptualizations and trends of innovation research in the literature can be traced to this definition and its context. For instance, Christensen (1997), and Tripsas and



Gavetti (2000) focused on creative destruction (i.e. the context of this definition) and investigated why established firms fail. Utterback and Abernathy (1975) focused on product and process innovation in their study of the dynamics of innovation, and Tushman and Anderson (1986) zoomed in on the method of production and analyzed the impact of an innovation on a firm’s competences. Thus the Schumpeter definition above is very general. As a result, I am going to derive a more specific conceptual and operational definition of innovation.

### Product development locus

From a project management perspective, product development can be viewed as consisting of the six subprocesses shown in Figure 3 below.



**Figure 3: Product development project management framework (Wheelwright et al., 1992; p. 135)**

As can be inferred from Figure 3, innovation in the traditional sense of the word is not represented in the framework. However, many problems arise in product development that call for different types of innovation. “The essence of [each] product and process development problem may be defined as a performance gap between current practice or designs and the desired target” (Wheelwright et al., 1992; p. 220). The problems could happen at the system, component or part level of a system, or could involve process layout or piece of equipment. *An innovation occurs when a new solution is found to close the gap between current practice or designs and requirements or desired target.* The

solution could be a process or product, and it could vary from radical to incremental solutions.

The mileage of the gap closed during product development varies by organization and the competitive market conditions. In many cases, companies have research and development labs and/or advanced technology development programs that help close the gap between performance and requirements. Depending on company policies, strategy, and competitive, market and technical imperatives, research and development labs work on problems ranging from basic science to applied research and development (Hauser, 1998). Other companies have advanced technology development programs where completely new technologies are developed to an acceptable technology readiness level (TRL) before they are incorporated into the product.

However, competitive conditions normally force companies to develop the technology and product concurrently (Krishnan & Ulrich, 2001) in order to enter the market faster. For instance Eisenhardt and Tabrizi (1995) reported that high technology products entering the market six months late were 33% less profitable over five years, while those that entered the market on time but 50% over budget were only 4% less profitable. Even technologies that pass the TRL test encounter robustness challenges that call for significant innovation during systems development (Clausing, 1994; Clausing & Frey, 2004).

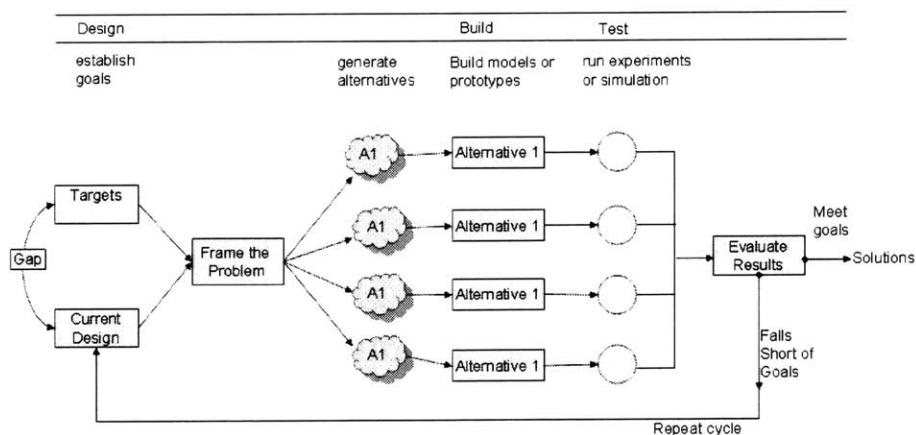
In the framework shown in Figure 3, innovation is often captured in the problem solving, prototyping and testing cell. The process is often achieved using the design-build-test framework (Clark & Fujimoto, 1991). The “build” is sometimes replaced with “model,” which is achieved with the help of new technology such as computer aided engineering and computer aided design.

## Design-build-test framework

In the *design-phase*, the developers frame the problem and set goals for the problem solving process. They then generate alternatives based on their understanding of concepts, relationship between design parameters and customer attributes.

In the *build phase* developers create prototypes that allow for testing. This can be done using materials that are easy to make depending on the phase of development. Early prototyping is usually done by industrial engineers and body engineers in order to establish the architecture. Middle prototyping is done by subsystem and quality engineers in order to set the subsystem, system and verification, and final prototyping is done by manufacturing process factory operations engineers. Early prototyping tends to be cheaper to produce than the pilot production units get more expensive.

The build phase is followed by *testing phase*. The tests could focus on a particular component, or could be full scale as in pilot production units and the associated pilot production system. Figure 4 below summarizes the problem solving cycle in product development.

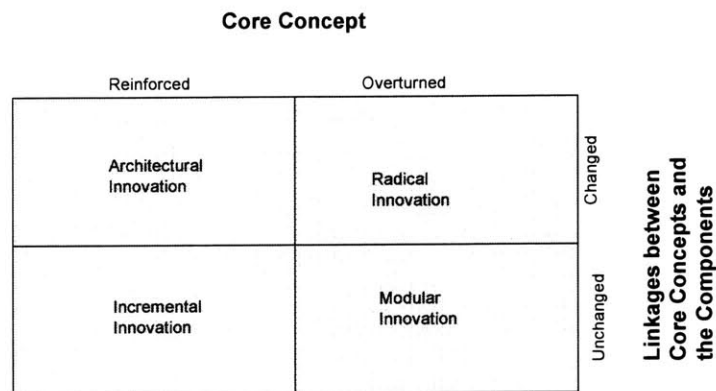


**Figure 4: Problem solving cycle in product development (Wheelwright et al., 1992; p. 223)**

The framework can alternatively be stated as design, build, run and analyze (Thomke & Fujimoto, 2000).

## Product innovation

As mentioned above, the new solution can be a product or a process. Given that I am interested in complex engineering systems such as aircraft engines and satellites, Henderson and Clark's (1990) framework of innovation is most applicable in this systems development context. Their conceptual framework divides innovation into radical, incremental, modular and architectural innovations based on whether the innovation changes the linkages among the different subsystems or whether the innovation changes the core concept of the specified subsystem. Each of these innovation types is illustrated in Figure 5 below.



**Figure 5: Innovation conceptual framework (Henderson et al., 1990; p. 12)**

### *Radical innovation*

In this framework, a radical innovation is one that changes both the design concept and subsystem linkages. As a result, it establishes a new architecture and/or dominant design. However, other researchers have defined radical innovation differently. For instance, Ettlie, Bridges, and O'Keefe (1984) broadly describe a radical innovation as one that requires an organization to go through large (in terms of magnitude or cost) changes. Rosenbloom and Christensen (1994) define a radical innovation as one that “draws on new or different science bases, or ... requires the development of qualitatively new technological capabilities within the innovating organization” (p. 658), and Dewar and Dutton (1986) define radical innovation as one that “contains a high degree of new knowledge” (p. 1422).

The differences in the definitions of radical innovation are largely driven by the different perspectives of the different authors. For example, Ettlie, et al. (1984) defined radical innovation from an organization perspective, while Henderson and Clark (1990) defined radical innovation from a product development perspective. Thus, one can visualize an innovation as being radical in  $m$  of its  $n$  ( $m \leq n$ ) dimensions, where each dimension is a different perspective on the innovation. Given my research context, I will retain the definition of radical product innovation as an innovation that calls for a new concept and changes subsystem interfaces.

#### *Architectural innovation*

Architectural innovation changes the way the different subsystems are linked together while leaving the subsystem core design concept (and thus the basic knowledge underlying the component) unchanged (Henderson et al., 1990; p. 10). Abernathy and Clark (1985) provide a slightly different definition of architectural innovation: “innovation that defines the basic configuration of product and process, and establishes the technical and marketing agenda...in effect, it lays down the architecture of the industry...” (p. 7). Similar to radical innovation, I will retain the product-system centric definition of architectural innovation by Henderson et al. (1990) above. They went on to argue that the impact of architectural innovation can be detrimental if firms fail to differentiate subtle architectural knowledge from the design concept knowledge. However, architectural innovation does not occur often once the dominant design has emerged.

Kevlar blade containment case is an example of an architectural innovation in the PW4098 context. Architectural innovation is relatively rare since the interfaces are standardized in order to enable system integration in modular design organizations.

#### *Modular innovation*

Modular innovation only changes the core design concepts of the product without changing the product architecture or the way the concepts are linked together. Modular innovations are common in modular systems. Engineers can work in one particular component (module) without requiring many changes in other components.

An everyday example of a modular innovation is the replacement of the ball-based computer mouse with the optical mouse. In this aircraft engine context, the Full Authority Digital Electronic Control (FADEC) is an example of modular innovation. The entirely electronic control replaced the partly mechanical controls that existed in earlier engine models.

### *Incremental innovation*

Incremental innovation is generally treated as the “opposite” of radical innovation. Instead of changing the core concept of a subsystem and the linkages among the different subsystems, incremental innovation reinforces the core concept and leaves the linkages unchanged (Henderson et al., 1990). Thus incremental innovation introduces minor changes to the existing product while the design concepts and linkages remain the same. Departure from existing practices is minimal, and it reinforces competence and capacity of the incumbent (Camison-Zornoza et al. 2004). Similar to radical innovation, there are several definitions of incremental innovation, but I will use the definition above because of its applicability in the system development context.

An incremental innovation in the case of the PW4098 engine resulted in the ability to raise the High Pressure Turbine temperature significantly (by 200 degrees) so as to provide enough thrust for the larger engine model.

### Hierarchy of product innovation

Since systems are fundamentally nearly-decomposable and hierarchical (Alexander, 1964; Simon, 1962; Simon, 1999) the operationalizations of radical, incremental, modular and radical innovation are hierarchical as well. That is, linkages between the different components can change at a subsystem level but not necessarily at the holistic system level. For instance, at the entire aircraft engine level, the last major radical innovation was arguably in the 1950s when commercial aircraft engines switched from turbojet to turbofan engines. At the subsystem, there are several radical innovations one of which is split shipment joint described above.

### The product innovation process

In investigating the impact of network structure on product innovation, it is useful to consider innovation as a process since current networks literature invariably simply treats innovation as an output. The product innovation process can be broken down into the generation of an idea, problem solving or development, and implementation and diffusion stages (Utterback, 1971, 1974). The idea generation stage is alternatively known as the initiation stage (Ebadi & Utterback, 1984), and other researchers separate the implementation and diffusion substages (e.g. Zmud, 1982). Based on Utterback's delineation of the product innovation process, I will briefly describe each stage as viewed through a communication/interactions lens.

The *idea generation* stage involves the synthesis of diverse information including information about the possible need (for need stimulated innovation) or technology (for technology stimulated innovation). Thus diverse ideas are a critical part of this stage. More often than not, the ideas are stimulated by needs, which are normally articulated by someone from outside the organization (Utterback, 1994). Nevertheless, technology is also a significant stimulant of innovation. The newer the technology, the more likely is technology to be the stimulant of the innovation than the need (Utterback, Allen, Hollomon, & Sirbu, 1976). Better yet, an exchange between the need (i.e. the "customer") and the technology (i.e. the "innovator") leads to better idea generation (Clark, 1985).

The *problem solving or development* stage involves setting specific technical goals, and designing alternative solutions to get "there" (i.e. results in a technical solution or prototype (Utterback, 1971)). This stage is equivalent to problem solving as described above. Communication in this stage tends to be more structured, with internal communication playing a more important role than external communication. Though some ideas in this development stage come from outside the organization, internally sourced ideas are more valuable (Allen, 1977), and external communication does not necessarily lead to better performance (Tushman & Katz, 1980).

The *implementation and diffusion* stage is the final stage in the product innovation process. Implementation involves manufacturing, engineering, tooling and plant and market startup required to bring an invention to its first use (i.e. it starts with the prototype and ends with the product (Utterback, 1971)). On the other hand, diffusion occurs in the environment once an innovation is introduced.

However, this framework of innovation is not strictly limited to product innovation. Technological process innovations such as new machinery can be manufactured and diffused as well. For example, Whitney (1995) writes that Sony developed its manufacturing in-house and sold them in the market. Thus a process technological innovation fits the framework described above.

### **Process Innovation**

Most innovation literature is focused on product innovation because product innovations are visible, prestigious and patentable in most cases (Damanpour & Gopalakrishnan, 2001). However, process innovations have a substantial impact on the enterprise (Pisano, 1996; Utterback, 1994). As Abernathy and Utterback (1978) argued, once a dominant design emerges, innovation activities shift from product to process innovation; hence process innovation can make or break a firm. Even the small process innovations are critical for the success of a firm. For instance, Hollander (1965) found that about half of productivity improvements at Du Pont Rayon Plants were attributed to unpatented process innovations, and Etlie and Reza (1992) found that integrated product-process innovations were positively related to increased firm success.

Process innovation is commonly defined as “new elements, equipment or methods introduced into the firm’s production system to develop a product or service” (Camison-Zornoza et al., 2004; p. 335). Utterback and Abernathy (1975) define the process more broadly as “the system of process equipment, work force, task specifications, material inputs, work and information flows, etc., that are employed to produce a product or service” (p. 641). Thus, one can generalize that process innovations are aligned with the mode of production of a good or service (Barras, 1986). Closely related to process



innovation is administrative innovation, which is innovation “that changes an organization structure or its administrative purposes” (Damapour, 1987; p. 677). Administrative innovation is related to human resources, coordination and control of the enterprise at the high echelons of the enterprise (Kimberly & Evanisko, 1981). The focus of this work is on process innovation.

The commonly used definition of process innovation above was developed in the context of explaining the industrial dynamics of innovation; hence researchers have often qualified the definition in order to explain ideas at other levels of analysis or explain more specific ideas. For instance, Pisano and Wheelwright (1995) used the term “manufacturing-process innovation” when they argued that manufacturing-process innovation is an integral part of product technological innovation. Likewise I am going to use the term “product development process innovation”, in describing process innovation during the development phase of the complex engineering systems. The term “‘product development process’ innovation” is a mouthful; hence I will refer to it as process innovation in this thesis.

Similar to the product innovation context, researchers have used the constructs “radical” and “incremental” to describe the impact of process innovation on enterprises (e.g. Ettlé et al., 1984). The constructs are not as operational and precise as the Henderson et al.(1990) constructs described above. In general, the literature implies that radical innovations call for large changes in the organization while incremental innovations call for small changes. Green, Gavin and Aiman-Smith (1995) proposed a four-dimensional measure of “radicalness” based on technological uncertainty, technical inexperience, business inexperience, and technology cost. The measure was developed as “a firm’s management would experience it [i.e. radical innovation]” (p. 203); hence it is not squarely applicable in the context of product development viewed from the low level engineers who develop the system.

A more useful classification of process innovation during the development of a complex engineering system is the classification into coordination / organization related

innovation and technical innovation. The coordination/organization aspect is related to the coordination of activities, procedures (specific sequence of activities/rules used by developers), process (broad sequence of activities), structures (formal organization) and principles (set of ideas and values for guiding decisions in development)<sup>5</sup>. The technical aspect is related to innovation in the technology used in product development. This classification is based on the fact that product development tasks largely consist of coordination and engineering (Clark et al., 1987; Clark et al., 1991). The engineering aspect involves a significant amount of trial and error (Marples, 1961) and experimentation (Thomke, 1998; Thomke, von Hippel, & Franke, 1998)

### The process innovation process

Because of the diversity in innovation research, there are several<sup>6</sup> frameworks that divide innovation into different subprocesses, but Zaltman, Duncan, and Holbek's (1973) framework is widely quoted. They divided process innovation into initiation and implementation stages, each stage with its own substages.

The *initiation stage* consists of the knowledge awareness stage where the relevant unit is aware of the new innovation knowledge. The knowledge awareness is followed by the attitude formation towards the innovation stage and finally the decision stage in which the organization processes lots of innovation in deciding whether they should implement the innovation or not. In summary the initiation stage “consists of all activities pertaining to problem perception, information gathering attitude formation and evaluation, and resource attainment leading to the decision to adopt” (Damanpour, 1991; pp. 562).

The *implementation stage* is concerned with the actual utilization of the innovation (Zaltman et al., 1973). The implementation is divided into two substages. In the initial implementation substage, the organization implements the innovation on a trial basis. If the trial succeeds, the initial substage is followed by the continued implementation stage. From a tasks point of view, “implementation consists of all events and actions pertaining

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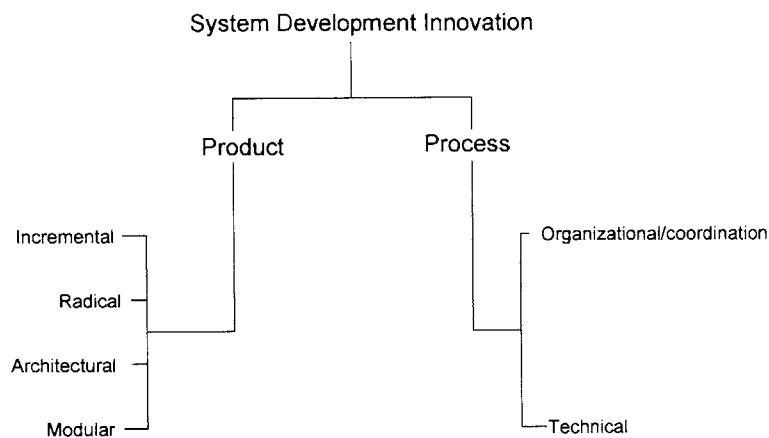
<sup>5</sup> The description of procedures, process, structure and principles is based on (Wheelwright and Clark, 1992; p. 296)

<sup>6</sup> Zaltman, et al., (1973) list eleven frameworks on pages 61-62.

to modifications in both an innovation and an organization, initial utilization, and continued use of the innovation when it becomes a routine feature of the organization” (Damanpour, 1991; pp. 562).

This process innovation process largely applies to the organizational aspect of process innovation. Nonetheless, some organizational process innovations can be diffused into the industry as well through trade literature or consultants. Thus the applicability of the framework is an approximate.

### Summary of operational definitions



**Figure 6: Summary of innovation types studied in this thesis**

- Innovation → An innovation in product development occurs when a *new* solution is found to close the gap between current practice or designs and the desired target.
- Radical product innovation → an innovation that calls for a new core concept and changes subsystem linkages or interfaces
- Architectural product innovation → an innovation that changes the way the different subsystems are linked without changing the core concept of the component
- Incremental product innovation → an innovation that neither changes the linkages nor the core concept of the subsystem

- Modular product innovation → an innovation that changes the core concept of a subsystem but leaves the linkages between the different component unchanged
- Organizational / coordination process innovation → process innovation with respect to the coordination or integration of activities during the development phase of a complex engineering system
- Technical process innovation → process innovation particular to the technology used during the development phase of a complex engineering system

## **Conclusion**

In this chapter, I defined and characterized different types of innovation from a complex engineering system point of view. Product innovation definitions and characterizations are largely based on whether an innovation changes the core concept or the way a component is linked to the rest of the system. I also explained the concept of product innovation hierarchy since it helps researchers understand the characterization of product innovation in a systems context. Furthermore, I clarified my focus on product development process innovation as opposed to the general “mode of production” innovation widely covered in the literature. Because various innovation stages require different communication or interaction strategies, I described the various innovation stages associated with each type of innovation.

In the ensuing chapter, I will review Design Structure Matrix (DSM) literature as a methodology for managing interactions during complex system development. I will propose the use of network analysis toolkits and metrics in systems development interactions, and review the nascent literature on networks and complex system development.

## Chapter 3: From DSM to Network Analysis

### **Introduction**

In this chapter, I will build on the previous chapter that defined innovation by linking innovation to the flow of technical information during the process of developing a complex engineering system. Following the literature-based establishment of the link between innovation and technical information flow, I will review Design Structure Matrix (DSM) literature with a focus on clustering and sequencing analyses as the major classes of algorithms used in DSM research. I will then propose the use of network analysis as a useful tool for extending DSM concepts and methodology. Network analysis enables researchers to quantify and be precise with research in innovation and complex engineering systems.

From a structure perspective, the chapter analogously starts with a brief literature review that links the flow of technical information and innovation. The review is followed by a description of what a DSM is, a review of clustering and a review of sequencing in DSM analysis respectively. The DSM section ends with absolute and comparative advantages and disadvantages of the DSM. The networks section follows the DSM section and it starts with a definition of networks followed by an exemplary equivalent representation of information as a DSM and as a network. The subsequent subsection reviews the application of networks in complex system development, and the chapter ends with an emphasis of the advantages of networks over DSMs.

### **Technical information flow and innovation**

As discussed in the previous chapter innovation is conceptually a process of creating new combinations (Schumpeter, 1934) that enable engineers to close the gap between current product or process performance and the desired performance. The new combinations are combinations of “materials and forces,” knowledge (Drucker, 1985), and information as Allen (1977) argued that engineers “transform information from the verbal form into a physically encoded form” (p. 2). Thus, technical information transfer is a critical part of

complex system<sup>7</sup> development, and innovation (Eppinger, 2001). However, systems inherently have many parts (Simon, 1962), and each part is associated with a problem solving activity during the development process (Alexander, 1964). According to von Hippel (1990) “problem solving that extends beyond a single individual involves communication and coordination among problem solvers” (p. 409). Because DSMs and networks play an important role in the capture and analysis of technical information, and coordination of design activities they are integral to the empirical of study innovation in complex engineering systems.

The relationship between technical information flows and innovation is further operationally incorporated into this thesis by the definitions of innovation discussed in the previous chapter. The definitions, primarily adopted from Henderson and Clark (1990), emphasized the impact of an innovation on subsystem linkages. Subsystems linkages are often reflected in the complex product development process structure (Baldwin et al., 2000; Nightingale, 2000; Sosa, Eppinger, & Rowles, 2004), and different aspects of the structure (i.e. the interconnectedness) are captured by the directed network structure and the DSM.

The rest of this chapter reviews the application of DSMs in complex product development, and proposes the increased use of network analysis as the next logical step in studying innovation in complex engineering systems.

### **What is a DSM?**

A DSM is an  $N^2$  diagram used to capture or represent interactions among different processes or tasks (Eppinger, Whitney, Smith, & Gabala, 1994), parameters (Sosa et al., 2004), organizational teams (Danilovic, 1999) or system components (Pimmler & Eppinger, 1994). The use of the  $N^2$  diagram in system design was first introduced by Steward (1981a; 1981b), and he coined the term “design structure matrix” for the matrix. As expected, the definitions of DSM slightly differ among researchers. For instance, Baldwin and Clark (2000) restrict the use of “DSM” to interactions among parameters

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<sup>7</sup>A *man made* complex system can be viewed as a “new combination” or a “physical embodiment of information” from the Schumpeter (1934) and Allen (1977) lines of thought respectively

and use the term “Task Structure Matrix” (TSM) to indicate the interaction among tasks or design processes. For this work, I will use the definition by Steward and its extension by Eppinger and his associates.

In its basic form, a DSM consists of a list of the same set of Integrated Product Teams<sup>8</sup> (IPTs) along the X axis and the Y axis. An interaction between IPT X and Y is denoted by a 1 in the (X, Y) cell. Zeroes or empty cells indicate that there is no information relationship between the two IPTs. The empty cell can also be regarded as an information filter (Baldwin et al., 2000). For example there is an information filter between C and D in the example in Figure 7 below. B provides information to D (cell B, D is marked) and D provides information to B (cell D, B is marked). In other words, there is a symmetric relationship between B and D, and the two are coupled or interdependent. On the other hand, the relationship between C and A is asymmetric with C providing information to A. To put it succinctly, row-elements contribute information to column elements. The diagonal elements are blocked since the relationship between a parameter and itself is not very meaningful.

	A	B	C	D	E
A					
B				1	
C	1				
D		1			
E		1			

**Figure 7: An elementary example of a DSM**

Not all interactions are of equal strength; hence the basic DSM can be improved by numerically indicating the strength of the ties among IPTs. Strong ties could be indicated using a 2 and weak ties using a 1. As an example, weak ties could be ties where the technical information is predictable so that an IPT can start developing its product or execute its task before another precedent task is completed. Strong interactions could be

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<sup>8</sup> Note that I am grounding this discussion on the interaction among organizational teams though one could have parameters, tasks or system components interacting instead of IPTs. The term IPT is used at Pratt and Whitney to denote cross functional product development teams. Other companies use different labels, for example General Motors uses Product Development Teams (PDTs).

ties where the information is unpredictable and can not start without information about a precedent task. Chapter 5 provides some more examples of tie strength definitions.

### **DSM Analyses**

In general DSM analyses have focused on clustering and sequencing interactions (Browning, 2001). Clustering enhances the system decomposition or integration process while sequencing increases product development speed. The following two subsections provide a detailed review of each class of DSM algorithms. Note that the algorithms are not mutually exclusive, sequencing algorithms often included a clustering function as well.

#### Clustering

Clustering algorithms are largely used on static DSMs, which are often IPT or parameter DSMs. The algorithms cluster off-diagonal elements by reordering DSM rows and columns. The objective function of the algorithm is to maximize interactions within a particular cluster and minimize interactions across clusters. Some algorithms also aim to minimize the size of the clusters. In the case of IPTs, the resultant cluster (also known as a block) could be the combination of small teams with high interactions into bigger teams or the division of a team into smaller teams. In the case of parameters, the DSM analysis could result in different decompositions of the system. Thus DSM clustering algorithms help in system modularization.

There are several clustering algorithms. For example, Pimmler et. al. (1994) used a distance-from-diagonal penalty algorithm, while Altus, Kroo, and Gage (1996) used a genetic algorithm. Since there are four types of parameter interactions (i.e. spatial, material flow, energy and information flow) in complex engineered systems (Pimmler et al., 1994), there could be four different maps of clusters. However, the importance of each set of interactions depends on the complex system and the researcher's intentions. In physical parameters' clustering, the information interactions are least critical since information can easily be rerouted.



Nevertheless, information flow is of primary importance in many clustering analyses among IPTs in complex product development. For instance, McCord & Eppinger (1993) did an information-based clustering analysis of the product development organization at General Motors. They found that some metateams had interfaces with several smaller teams and identified those teams as the integrating teams.

The advantages of proper decomposition or integration are numerous. Primarily, informed decomposition can reduce coordination complexity. Decomposition also simplifies some complex problems by breaking them into smaller manageable problems. Since the complex engineering system cannot be developed at once because of its complexity, and can not be developed serially because of time constraints, a good decomposition influences the product development time, time to market etc. Additionally, the process of building a DSM increases system-wide understanding and provides a platform for discussing coordination changes to the product development organization.

### Sequencing / Partitioning

Time based DSMs indicate the flow of a task in time by the order of the rows and columns, and the DSMs are typically analyzed using sequencing algorithms (Browning, 2001). Partitioning resequences the design activities so as to maximize information available at each stage of the design process (Gebala & Eppinger, 1991), and hence reduce feedback among the design activities. The unwanted feedback can also be minimized by reducing its scope and this is achieved by block diagonalization (also known as block triangularization) of the matrix.

Several algorithms are used for the partitioning process. Ledet and Himmelblau (1970) used matrix algebra, Rogers (1989) used a rule based algorithm which he later updated to include genetic algorithms in Rogers (1996), and Steward (1965) used a loop tracing procedure algorithm. Gebala and Eppinger (1991) designed an algorithm that schedules independent tasks first (empty rows and columns), identifies loops by path searching (i.e. tracing the flow of information until a task is encountered twice) or by the powers of

adjacency matrix and represent the tasks in a loop as a single task. If some tasks remain unscheduled, the algorithm repeats the process.

In an ideal case, all marks are pulled to the lower triangle<sup>9</sup> while those that can not be pulled into the lower triangle, are pulled as close to the diagonal as possible where they are grouped into blocks (Steward, 1981b). There are several strategies for dealing with coupled tasks inside a block besides collapsing them into a single task as practiced in Performance Evaluation and Review Technique (PERT). Collapsing the tasks into one task does not help the actual design activity since it only results in *apparent* simplicity. More effectively, tasks that remain in a block (i.e. coupled or interdependent) can be performed as a group, and information transfer would have to occur as a continuous negotiation process. Alternatively, some tasks from the block can be done much earlier in the process and thus change the definition of some earlier processes. Some tasks could be split based on domain knowledge, or decisions points can inserted based on domain knowledge as well. Tearing also allows engineers to control feedback loops within a block. It allows designers to make assumptions about certain tasks so as to allow the task scheduling process to proceed. Assumptions are made about activities with the least scope first, the matrix repartitioned and the process repeated if feedback loops remain.

Tearing has received a significant amount of attention in DSM-based research. As outlined above, engineers can use domain knowledge to identify tasks whose information can be estimated. If the results are not satisfactory, heuristics can be used in tearing algorithms (e.g. Rogers, 1989). Alternatively, tearing algorithms schedule tasks with minimum input streams (minimum row elements) first. If that fails, the algorithms schedule tasks with maximum number of outputs, and if that fails, the algorithm schedules the task which takes the largest number of steps to reach all other tasks under consideration (Gebala et al., 1991). There are several mutations of this algorithm. For instance Grose (1994) used an algorithm that tries to move activities downstream without causing additional iterations.

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<sup>9</sup> I am adopting the convention that information flows in counter clockwise direction. Some researchers such as Browning (2001) use the convention that information flows in a clockwise direction.

Besides identifying feedbacks, iterations and activities that can be done in parallel without increasing the amount of iterations, process DSMs generally help by illuminating interactions associated with a particular task (Browning, 2001). However, the ability to use the DSM depends on the ability to determine the process boundaries, and the decomposition of the process. On the other hand, parameter identification is relatively simple.

Sequencing is also practiced in parameter-based DSMS. The sequenced parameter-based DSMs help engineers to avoid performance degradation of downstream parameters based on decisions made upstream (Krishnan, Eppinger, & Whitney, 1997).

### **Other application of DSMs**

There are several other applications of the DSM besides the applications described above. For example, Smith and Eppinger (1998) used the dependencies in a DSM to calculate the amount of time that it would take to complete a task and suggested ways for minimizing that time by either sequential or concurrent design. Glynn and Pelland (2000) used the DSM to analyze the impact of a reorganization exercise on information and knowledge flow at Pratt and Whitney. They found that communication was hampered by the extended amount of time spent in transit to-and-from meetings in different locations in Connecticut.

### **Advantages of the DSM**

As indicated above, advanced analysis of the DSM allows one to decouple, resequence, split, condense tasks or insert decision points in order to improve the flow of technical information (Eppinger, Whitney, Smith, & Gebala, 1990). Besides that, the DSM acts as a clear visual tool that enables one to see the interactions among parameters and their respective IPTs. It also enables engineers to determine the importance of each parameter to other parameters with respect to design information, and leads to better system decomposition and integration.

Compared to similar tools such as the Program Evaluation Review Technique (PERT) and the Critical Path Method (CPM), the DSM does not ignore feedbacks and iterations among the different tasks. Compared to a directed graph, the DSM shows the underlying structure of the design activity while the directed graph does not. The directed graph shows the statistical properties of the interactions/communication network.

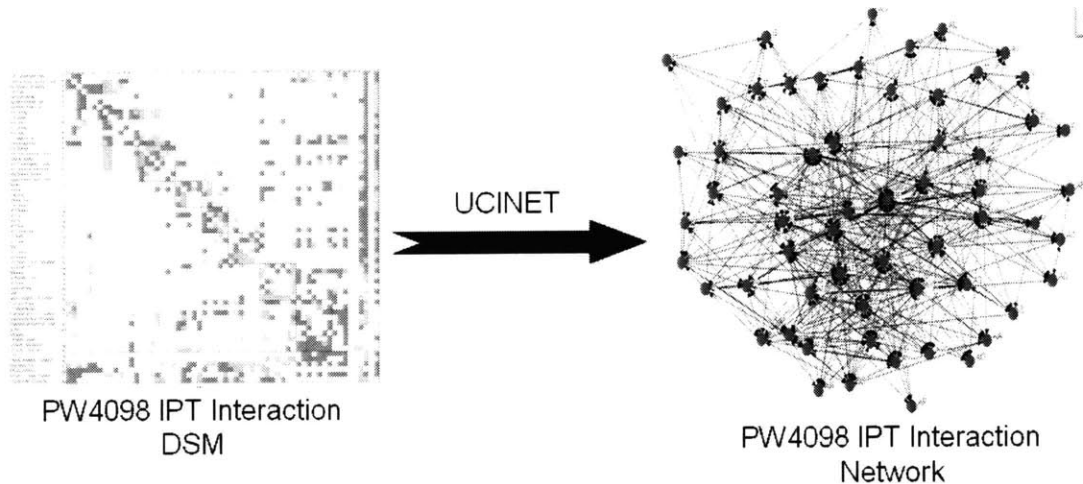
### **Limitations of the DSM**

A single DSM only shows one process flow, and does not show all process paths. As the number of interactions grows, the interactions quickly become intangible. As a corollary, it becomes difficult to visualize interactions represented in the DSM format. In terms of analysis, DSM analyses require large amounts of data and the process of getting the data can consume a lot of resources and time. Additionally the ordering of parallel activities within a given block depends on the algorithm used. Thus the sequencing within a given block is more of an art than a science.

Compared to the Quality Function Deployment (QFD) (Akao, 1990) and the Design Matrix (DM) (Suh, 2001), the DSM can not be used to analyze across multiple dimensions. For example, DSM analyses focus on interactions among like-elements (e.g. tasks) while the DM analyzes the interaction between parameters and related functions. Additionally, the DSM does not clearly show overlapping tasks unlike a Gantt chart. Finally, and most pertinent to this research, the DSM does not have quantifiable metrics that we can directly use to study innovation.

### **Networks analysis in product development**

The same information contained in a DSM can be depicted in the form of a directed network (digraph). There are undirected networks as well, but networks in product development are directed because receiving technical information in systems development is not the same as sending the technical information. Figure 8 below presents the same information in a DSM and in a network for illustration purposes.



**Figure 8: Illustration of the equivalence between a DSM and a directed network. The diagram is based on data<sup>10</sup> from Rowles (1999), and I used UCINET (2005) to convert the DSM into the network**

As I discussed above, the DSM analyses have predominantly involved task sequencing in order to achieve faster product development, and clustering for better system decomposition. From the sequencing dimension, a lot of rigorous work has been done on tearing as a means of “decoupling” coupled activities. Thus employing the network representation enables researchers and engineers to employ social network analysis which have not been applied in the product development extensively. Moreover, the availability of networking data and increased computing power will enable researchers to use networks analysis toolkits much more fully than was done in the 1960s and 1970s.

The metrics and statistical mechanics methodologies developed by sociologists have been improved and applied in other fields such biology and condensed matter physics already. They have also been applied in studying other networked systems such as the power grid (Watts & Strogatz, 1998), software architecture (Valverde, Cancho, & Solé, 2002), metabolic and protein networks (Jeong, Mason, Barabási, & Oltvai, 2000), and many other systems.

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<sup>10</sup> Note that I am using the data for illustration purposes without getting into a data validity and reliability debate.

In systems development, Braha and Bar-Yam (2004) were among the first to explicitly use network analysis. They focused on describing the topology of the complex system development network, and argued that the network had small world characteristics, was sparse, and had scale free properties. The small world characteristics are the relatively short average path length and the high clustering coefficient. For instance the network in Figure 8 has a path length of 2.02. This means that the average number of links (edges) between any two nodes is 2.02. The clustering coefficient (C) of the network is the average clustering coefficient of each node. The clustering coefficient ( $C_i$ ) of a node  $i$  in a directed network is defined as the number of links ( $m_i$ ) among its  $k_i$  neighbors divided by the total number of possible links among the neighbors i.e.:

$$C_i = \frac{m_i}{(k_i - 1) k_i}$$

**Equation 1**

$$C = \frac{1}{N} \sum_{i=1}^N C_i$$

**Equation 2**

The average clustering coefficient Equation 2 of the network in Figure 8 is relatively high at 0.49. The high clustering coefficient indicates the tendency towards modularity in system development networks. This is because complex systems are generally designed as components with many links among subcomponents in the component and fewer links among components where possible. Thus the number of linkages among  $k_i$  neighbors is high by design, and as can be seen in Equation 1, the clustering coefficient will be high. Thus like other small world networks, a system design network tends to have a *short* average path length and *high* average clustering coefficient. The adjectives *short* and *high* are based on comparison with computer generated random networks<sup>11</sup>.

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<sup>11</sup> Braha et al. (2004) generated four different random networks. The average clustering coefficient ranged from 0.021 to 0.070, and the average path length ranged from 2.583 to 3.448.

In discussing the scale-free properties of the network, Braha et al. (2004) focused on the power law degree distribution. The degree of a node is the number of links on that node. In-degree is the number of in-directed links, while out-degree is the number of out-directed links. The power law states that a few nodes are highly connected while the average node is not as highly connected (Barabasi, 2000; Watts, 2003). In laymen's terms, the power law approximates to the statement that the rich get richer. Thus, one observes very few key nodes with a very high number of links, while the average node has a relatively small number of links.

However, there is a cut-off in both the in- and out- degree distributions, with the in-degree cut-off much lower than the out-degree cut-off. The cut-offs are due to the cost of a link between nodes, limited information processing capability because of bounded rationality (Simon, 1957), and limited node capacity. Since the in-degree cut-off is lower, the cost of adding an in-directed link is much higher than its out-degree equivalent (Braha et al., 2004).

Beyond description of the network in complex system development, network theory has been used to define modularity (Sosa, Agrawal, Eppinger, & Rowles, 2005), and identifying IPTs that are important with respect to information flow (Batallas & Yassine, 2004). The key contribution of network theory in the work of Sosa, et al. was the ability to *quantify* and provide a more *precise* definition of modularity. Since Batallas et al's (2004) procedure for identifying key IPTs is similar to Allen's (1977) procedure (see pages 143-144 or (Allen & Cohen, 1969)) their contribution was the ability to *quantify* the information importance.

## **Conclusion**

In this chapter, I first built on the previous chapter that defined innovation by linking innovation to the flow of technical information during the development of complex engineering systems. Since the DSM is a prominent tool used in analyzing interactions in systems development, I reviewed DSM literature with a focus on clustering and sequencing analyses as the major classes of analyses used in DSM research. I then reviewed advantages and disadvantages of the DSM before I introduced network analysis

as a useful tool for further research. I also reviewed the nascent literature on network analysis in product development research. I concluded that similar to early research in interorganizational networks, the current literature on networks and product development treats the network as a dependent variable, and largely describes the network structure with increased precision and quantifying capabilities imported from network analysis.

The next chapter contributes towards using the network structure as an independent variable in explaining innovation. I will review literature that empirically analyzed the link between networks and innovation outside the product development context, and then pose hypotheses based on the gap in literature.



## Chapter 4: Point of Departure and Hypotheses

### **Introduction**

In this chapter I will provide a short literature review focusing on interorganizational networks and innovation, and social networks and innovation as departure points for my research. The literature review reveals that most networks literature simply treats innovation as an output. It neither considers the different types of innovation nor does it consider innovation as a process. As a result, I will develop a set of five hypotheses that takes into account the different types of innovation as well as the different stages of the innovation process. The hypotheses are tailored towards a modular systems development organization.

Structurally, the chapter starts with the point of departure, which is divided into interorganizational networks, and social and other networks. This is followed by a synthesis section that identifies and frames the gap in the literature. Hypotheses come after the description of the literature gap. The first set of hypotheses is based on strong ties among IPTs and the initiation or idea generation phases of process and product innovation respectively. The second and final set of hypotheses concerns network density and product technological innovation.

### **Point of departure**

Interorganizational networks and social networks are the two prominent streams of literature on modern networks and innovation. As a result, I am going to briefly review the intersection of each stream of literature and innovation. I will also include seminal works in communication networks among research and development teams. The literature is applicable in the context of IPT networks because of the similarities in mechanisms that logically explain how the structure of a network leads to innovation.

#### Interorganizational networks and innovation

In interorganizational network research, most of the earlier contributions focused on explaining the emergence of interorganizational network as an organizational form

different from markets and hierarchies (Ouchi, 1980; Williamson, 1991). This interest in interorganizational networks was driven by the desire to explain Japanese industrial success of the 1980s. Thus the interorganizational network was largely treated as the dependent variable in these early years.

In the 1990s researchers started considering the interorganizational network as an independent variable and tried to explain various organizational phenomena such as improved organizational performance based on the embeddedness of the organization (Uzzi, 1996, 1997). Likewise there was interest on how the interorganizational networks influence innovation. For instance Freeman (1991) synthesized research issues in innovation networks, and Shan, Walker, and Kogut (1994) studied how cooperation among biotech startups affected innovation and found that the number of an ego firm's cooperative arrangements was positively related to innovation. Other researchers such as Kogut (2000), and Powell, Koput and Smith-Doerr (1996) got closer to innovation mechanisms in networks by explicating the role of interorganizational networks as sources of knowledge within an environment characterized by rapidly changing technology.

In investigating the impact of interorganizational network structure on innovation, Ahuja (2000) was among the first to consider other elements of the structure besides the number of cooperative arrangements among firms<sup>12</sup>. Using an interorganizational network of large chemical companies and awarded patents, he found that innovation was positively related to direct and indirect ties of the ego (focal) firm. Direct ties are direct alliances between an ego firm and its alter, while indirect ties are ties removed by one tie from the ego firm. An ego network is a network based on sampled focal firms (egos) and an alter is a firm in that network which is not a focal firm (Marsden, 1990). The IPT network described in chapter 1 is a complete network because all ties among population members are recorded.

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<sup>12</sup> The paper was based on his 1996 PhD thesis at the University of Michigan

Ahuja (2000) argued that depending on the type of alliance, direct ties increased access to resources<sup>13</sup> and information while indirect ties largely increased access to information. However, the effect of indirect ties was mediated by direct ties because “firms with many direct ties, being in the thick of things, are less likely to *add* to their knowledge or to absorb as much knowledge through their indirect ties than are firms with fewer direct ties” (p. 431).

Ruef (2002) investigated how the structural and cultural embeddedness of small organizational startups influenced the startup’s organizational innovativeness. From the structural portion of the study, he found that weak ties, team size and network diversity supported innovation while strong ties did not<sup>14</sup>. Based on a study of Canadian network of mutual fund organizations, Zaheer and Bell (2005) added that not only did the innovativeness of a firm depend on its structural position, it also depended on the particular firm’s characteristics. They further argued that firms with higher absorptive capacity (Cohen & Levinthal, 1990) and superior capabilities were better positioned to take advantage of their structural embeddedness in order to boost their performance.

Owen-Smith and Powell (2004) added geographical propinquity in analyzing the flow of knowledge in interorganizational networks for innovation. They argued that membership in a geographically concentrated network improved the innovativeness of the firm, while the centrality of the firm in a geographically dispersed network improved the firm’s innovativeness. The centrality of a firm in a network is measured by the number of its ties. In a concentrated region, there are more knowledge spillovers from the informal network and employee mobility, whereas firms in a dispersed region rely more on formal

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<sup>13</sup> Some alliances allow for sharing resources such as research, marketing capabilities in a particular niche etc and these can only be accessed via direct alliances. On the other hand, information can be accessed from indirect alliances because it is much more fluid. Word of mouth can easily spread through indirect ties while research capabilities are unlikely to spread indirectly.

<sup>14</sup> Ruef’s measure of tie strength is in line with Granovetter’s (1973) measure of tie strength. Family members were considered as strong ties while business associates, customers or suppliers were considered as weak ties. Network diversity was calculated based on the number of external advisors that each team had, and team size was measured as the number of people in each team. Note, I will consider tie strength in more detail in the “strong ties and innovation” section below.

ties than informal ties. By similar spillover reasoning, they argued that membership in a network dominated by public research organizations increased a firm's innovation output.

#### Social and other networks, and innovation

Though most social networks research has been devoted to sociological phenomena, there are seminal works that are applicable to the innovation context. These works have addressed processes that depend on search such as the job searching process. In a study of how experienced people found jobs, Granovetter (1973) found that weak ties were more important than strong ties for locating job opportunities. The strength of a tie was defined as “combination of the amount of time, the emotional intensity, the intimacy and reciprocal services that characterizes a tie” (p. 1361). The reasoning behind this finding was that people strongly tied had access to the same information while people weakly tied had access to diverse information. By the same reasoning, weak ties are better at bringing diverse ideas for innovation or diffusing innovations.

However, Burt (1992) argued that it was the chasm spanned by the weak tie that was important for the search process, and hence for innovation output. Thus the utility of the link between nodes *a* and *b* in Figure 9 below does not lie in the strength of the tie per se, but in the network gap between the blue and the white cluster of nodes i.e. the structural hole. “The weakness of a tie is a correlate and not a cause” because the tie between *a* and *b* could be strong (Burt, 1992; p. 28). Because the clusters are disparate, the nodes in each cluster have access to different types of information which brings different points of view to problem solving in innovation. Based on this argument, researchers generally find that structural holes in a network lead to increased innovation in that network. As a correlate, individuals or firms spanning a structural hole tend to perform better due to their access to diverse information (Burt, 1997, 2004).



**Figure 9: An illustration of the structural hole and weak tie argument**

However, as Ahuja (2000) pointed out, too many structural holes lead to increased malfeasance and opportunism which reduces innovation in interorganizational networks. Thus, Coleman (1988; 1990) argued that dense ties in a network lead to a sense of closure which in turn lead to increased trust, norms and sanctions against opportunism. These “virtues” lead to more innovation. Gulati (1995) added that the developed trust “obliges firms to behave loyally,” and Zaheer and Venkatraman (1995) added that dense ties lead to less costs of managing the network. Nonetheless, the increased trust comes at the expense of different perspectives on problem solving, and empirical tests tend to support Burt’s structural hole argument.

From communication networks in R&D labs, Allen (1977) found that the average engineer made little use of external scientific and professional literature, and that there was an inverse relationship between performance of an engineer and the use of external information. Additionally, intraorganizational communication were associated with higher performance compared to extraorganizational communication because of the coding scheme mismatches in extraorganizational communication (March & Simon, 1958). This was corroborated with the finding that when engineers sought ideas inside and outside the lab, ideas from within the lab were ranked more valuable than ideas from outside the lab (Allen, 1977). But no organization is self-sustaining; hence, there are gatekeepers who translate information between the organization and external community of scientists and engineers (Allen et al., 1969). The gatekeepers also translate information from the organization to the external world.

However, Tushman and Katz (1980) argued that not all projects require gatekeepers. Gatekeeper-mediated communication was important for projects that were locally oriented (i.e. where external sources were likely to use different coding schemes, values, norms and languages). For globally oriented projects, individual engineers' direct communication with the external community was directly related to success because occurrences of misinterpretations introduced by different languages and norms were minimal. Thus gatekeeper-mediated communication "hinges on the existence of a communication impedance and the associated communication boundary separating the subunit from external information areas" (Tushman et al., 1980; pp. 1073).

Some researchers investigated the issue of external communication from a different angle. From an *information processing paradigm*, they concluded that gatekeepers increased the amount and variety of technical information, and from a *political* point of view, strong managers enhance the flow of the resource (Brown & Eisenhardt, 1995). They also argued that in product development, the presence of cross functional teams reduces the need for gatekeepers because the research engineers are already exposed to external ideas to some level.

### **Synthesis**

Based on this review, there are four opportunities for making an academic contribution. The first contribution results from the fact that researchers in interorganizational and social networks have invariably treated innovation as an output; hence by treating innovation as a process, we can get new insights on the impact of the network structure on innovation. As I discussed in chapter two, the innovation process consists of different subprocess or stages, and each stage possibly thrives under a particular network structure. In the case of product technological innovation, I am most interested in the development or problem solving phase (Ebadi et al., 1984; Utterback, 1974) and for product development process innovation, I am interested in the initiation and initial implementation stages (Damanpour, 1991; Zaltman et al., 1973).

More specifically, the first contribution is in evaluating the impact of network structure on the development phase of technological innovation as opposed to the idea generation

stage, which is widely researched as shown above. Since coordination and engineering are the major tasks in product development organization (Clark et al., 1987), engineers spend more of their time developing ideas than generating new ideas (Marples, 1961); hence the innovation development stage is important.

For the second contribution, I hypothesize that not only does the network structure have different types of impact on different innovation substages, it also has different impact on different types of innovations. As Meyer and Goes (1988) empirically argued that “including innovation attributes in the studies of [innovation] adoption and implementation has considerable merit<sup>15</sup>” (p. 916). Current networks literature has largely overlooked the different types of innovation; hence there is an opportunity for an academic contribution.

The third contribution is the holistic analysis of how network structural properties influence innovation where the nodes are cross functional product development teams and the interactions are flows of technical design and development information. Most of the network-centric innovation research has focused on interorganizational and social network levels of analysis. Thus this work has the opportunity to contribute towards a somewhat neglected product development team mesolevel. As exemplified by Allen’s work (e.g. Allen et al., 1969) research has been done on research teams and communication but product development teams have the potential to be different because “science consumes and produces information in the form of human language, [while] engineers transform information into a physically encoded form” (Allen, 1977; pp. 2). He continued “This difference in orientation, and the subsequent difference in the nature of the products of the two, has profound implications for those concerned with supplying information to either of the two activities” (pp. 3)

Finally, network analysis allows researchers to quantify some properties/characteristics of modular design organizations that researchers could not quantify before importing

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<sup>15</sup> Note that Meyer and Goes (1988) were writing from the organization science world where the adoption process corresponds to Zaltman’s (1973) initiation stage, and implementation is the utilization of the adopted innovation as in Zaltman’s case. I am making the assumption that equivalent characterizations of innovation are important for studying product innovation as well.

network analysis into the design of complex engineered systems. As I discussed in chapter three, research in interactions among product development teams' interactions has been confined to the Design Structure Matrix world. Most of the work in that realm has *not* looked at the impact of network structure on innovation. Thus by using networks to study innovation in the systems development context, we make two related contributions: quantify new metrics suitable for studying innovation, and directly study innovation using those metrics.

### **Strong ties and innovation**

In general, the strength of a tie or a link between two sociological nodes has two dimensions: frequency of contact and emotional closeness (Burt, 1992; Granovetter, 1973), and the two dimensions are orthogonal (Marsden & Campbell, 1984) in social networks. In the case of product development teams, the emotional closeness is replaced with the “criticality of information needed to fulfill functional requirements” (Sosa et al., 2004), or some other “work-related” definition (e.g. Hansen, 1999).

From the strict frequency dimension of tie strength, coordination is improved through repeated exchange among members of a group (Kogut, 2000). The strongly tied IPTs “develop principles of coordination that improves their joint performances” (Kogut, 2000; pp. 407), and are more likely to jointly solve problems (Uzzi, 1996). Strong ties also enable the transfer of both simple and complex<sup>16</sup> knowledge while weak ties work best when transferring simple codified knowledge (Hansen, 1999). Additionally, the frequent contact leads to sharing more than information (know-what) but know-how as well (Kogut & Zander, 1996; Uzzi, 1996). Know-how is procedural compared to information (know-what) which is declarative (Kogut et al., 1996); hence I expect to observe a relationship between process innovation and strong ties that I will not observe between product innovation and strong ties.

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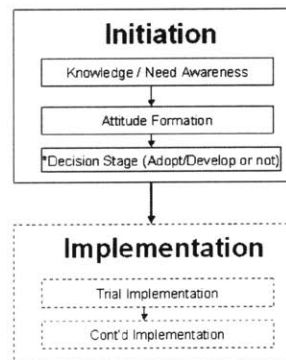
<sup>16</sup> Hansen (1999) used the degree of codification i.e. the extent to which the knowledge is fully documented or expressed in writing, and the extent to which knowledge is a set of interdependent components (pp. 87) to measure the complexity of knowledge.



Thus from Allen's (1997) definition of coordination technical communication, one can expect the strong ties to supply more than simple information for coordination but knowledge as well, while weak ties largely supply discrete information for coordination. I am going to investigate the impact of this knowledge aspect of strong ties on both product development-process innovation and product innovation. I will specifically focus on the initiation/idea generation stage and the initial implementation/development stages of innovation.

Initiation / idea generation stage of innovation

In chapter two, I divided process innovation during the product development phase of a complex system into two: coordination/organization related innovation and technical innovation. The coordination/organization aspect is related to the coordination of activities, processes, procedures etc while the technical aspect is related to innovation in the technology used in product development. I argue that strong ties are more likely to influence the coordination/organization and technical process innovation more than product innovation at the initiation stage.



(Zaltman et al 1973, Damanpour 1991)

**Figure 10: Process innovation substages**

Before proceeding, it is important to note the difference between product and process innovation. Product innovation is aimed at the market or customers, while process innovation is internally focused, primarily on efficiency (Utterback et al., 1975). Thus process innovations are more internally driven than product innovations (Ettlie et al., 1984). Additionally, process innovation tends to be organization specific while product innovation is industry specific (Damanpour et al., 2001). A process innovation has to fit

well with the rest of the organization, while product innovation largely has to fit the industry and the organization that produces the product to a certain extent. Because of these properties / characteristics of process innovation, I am going to argue that strong ties in the product development organization are more likely to influence the *initiation* phase of process innovation than the idea generation phase of product innovation.

Both process and product innovations are either initiated by awareness of a need or awareness of a means / opportunity. Utterback (1971; 1974) argued that needs stimulate innovation more often than the means. He reported proportions of need stimulated innovations ranging from 61% to 90%, and proportions stimulated by technical opportunities ranging from 10% to 34% (Utterback, 1971; pp. 622). The probability of having a means / technical opportunity initiated innovation increases with the novelty of the technology or industry. In process innovation, the need is internal to the firm, and is captured in the definition of strong ties by the criticality dimension of tie strength.

However, it is not only the amount of available knowledge i.e. strong ties that is useful in this initiation stage of innovation because the initiation stage is more of search than a transfer process. Similar to other search processes, the diversity of knowledge matters. In network analysis, this diversity of knowledge is often captured by the availability of structural holes as discussed above. The presents of a structural hole is often indicated by the absence of cohesion and structural equivalency redundancy.

Two contacts are cohesively redundant if they are connected by a strong relationship, and two contacts are redundant by structural equivalency if they have the same set of contacts (Burt, 1992). The redundant fraction of a relationship can easily be measured, and subtracting the redundant fraction from one yields the non-redundant portion of the relationship. The *effective size* of a network is the summation of the non-redundant portions of each node's primary contacts (see Burt, 1992 pages 50-53 for details). The effective size of a network is easily calculated using network analysis software such as UCINET (Borgatti et al., 2005).

In summary, the availability of more knowledge (more strong ties) and the diversity of the knowledge flowing in the ties (larger effective network) will lead to more process innovation initiation. At an applied level, the diversity of the knowledge can be captured by having some IPTs at key supplier facilities, partners or IPTs whose ties are not cohesively redundant. Such practices tend to increase the structural holes in a network. In network terms, this hypothesis can be summarized as:

*Hypothesis 1: Given similar effective networks, IPTs with more in-directed strong ties will have more process innovation than IPTs with fewer in-directed strong ties.*

In non network-centric but less precise terms, this hypothesis argues that given two IPTs with ties to the roughly the same *number* of key suppliers or partners or other IPTs within the firm that are not part of the IPTs core cluster, the IPT with more strong ties will have more process innovation.

Nevertheless, the amount of process innovation generated by strong ties is likely to level off after a given point. The leveling off is due to a cut-off in the number of strong and weak ties directed towards a given node in engineering systems (Braha et al., 2004). Intrinsicly, the cut off is due to human bounded rationality (Simon, 1957). Additionally, as the number of strong ties increases, the flexibility of the IPT might decrease due to binding (Hansen, 1999). This second phenomena plays a less prominent role because engineering systems networks are sparse (Braha et al., 2004).

However, *ceteri paribus* an IPT is likely to acquire better know-how for innovation from an innovative IPT compared to a non-innovative IPT. Two blind men leading each other are unlikely to get far.

*Hypothesis 2: Given similar effective network and number of in-directed strong ties, IPTs linked to other IPTs with more process innovation will have more process innovation than IPTs linked to IPTs with less process innovation.*

A version of hypothesis 2 has been posed before at the interorganizational network level. Zaheer et al. (2005) did not find empirical evidence for the hypothesis while Stuart (2000) proved the hypothesis in an ego network where the ego was a big semiconductor firm in alliance with a relatively small alter. Zaheer's (2005) analysis did not include tie strength as defined above, and I argue that tie strength is an important element of testing the hypothesis. An IPT is likely to learn more from a strong tie connection than a weak tie connection given similar access to structural holes.

The third hypothesis is based on the possibility that the degree of a node is simply due to innovation, and not the other way round. IPTs generating more innovation than the average IPT could simply need more knowledge and information for coordination.

*Hypothesis 3: An IPT's amount of both process and product innovation explains the IPT's degree i.e. the amount of innovation associated with an IPT induces the amount of its links.*

#### The initial implementation or development stage of innovation

The initial implementation or development phase of process or product innovation respectively is more of a knowledge and information transfer process than the initiation/idea generation stage. Hansen (1999) showed that strong ties enable the transfer of complex knowledge and lead to faster product development. Thus the importance of strong and weak ties has been empirically tested for product innovation development. There is no reason to assume that the need for transferring complex information would differ between process innovation initial implementation and product innovation development.

#### **Network Density and Technological Innovation**

As discussed above, weak ties (Granovetter, 1973) and the associated structural holes (Burt, 1992) have been empirically proven valuable for the search processes because they enable access to diverse information and knowledge. Both are associated with low density. Thus researchers such as Rowley, Behrens and Krackhardt (2000) have argued

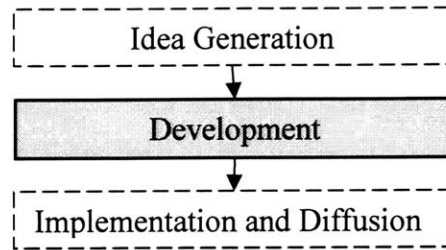
that low local density in interorganizational networks positively affects output where exploration is important while high local density positively affects output where exploitation is more important. An exploitation strategy favors the use of existing resources, knowledge and information while exploration favors experimentation with new knowledge, resources, and uncertain alternatives (March, 1991). Thus the influence of network density on the innovation process depends on the innovation phase under consideration because different phases require different mixes of the exploitation/exploration strategies. Using this line of thought, one could argue that the development of a product technological innovation is better served by high network density than low density. However, I argue that the impact of the network density in engineering systems depends on the type of technological innovation under consideration. In order to refine this hypothesis at the technological level, I am going to review the access to resources innovation mechanism a little more.

Utterback (1974) and the SAPPHO studies (Robertson, Achilladelis, & Jervis, 1972) argue that size does NOT necessarily affect innovation, innovation is influenced by the amount of resources that a firm (be it small or big) devotes to the innovation process. Likewise, network size has very limited impact on the development of an innovation unless teams working on the innovation have access to other parts of the enterprise. Given that the size of a network is the number of nodes in the network and density is the number of existent links among the nodes divided by the total possible number of links, density offers a refinement of the size metric in the networks environment. By combining the two streams of thought, we get to refine the relatively coarse treatment of innovation in the networks world.

As defined in Chapter 1, it is fair to argue that inter-IPT networks are more a pattern of knowledge and information flow than material resources, knowledge and information flow<sup>17</sup>. IPTs within the same design enterprise have access to the same enterprise

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<sup>17</sup> This follows from an earlier discussion where strong ties are associated with the flow of know-how and know-what, which are constituents of knowledge (Kogut and Zander, 1996; pp. 503) while weak ties are mostly associated with the flow of know-what, which is mostly information. Hansen (1999) added



**Figure 11: Phases of technological innovation (Utterback, 1971, 1974)**

resources which do not necessarily reside within one of the IPTs in the development organization. From coordination, and knowledge and information (i.e. strong and weak ties) perspectives, the impact of density on innovation depends on the type of innovation. Based on the Henderson and Clark (1990) framework of technological innovation, I argue that higher density is positively correlated with the development (defined in Chapter 1 as involving setting specific technical goals, and designing alternative solutions in order to get “there” (i.e. results in a technical solution or prototype (Utterback, 1971)(see Figure 11 below)) of radical or architectural innovations, and it is not positively correlated with the development of incremental or modular innovation. This is because incremental and modular innovations do not change the systems linkages; hence there is less need for coordination in order to implement either the modular or incremental innovation: an IPT can work in “isolation” given that the engineering system is nearly decomposable (Simon, 1962). On the other hand, radical and architectural innovations require a change in systems linkages / interfaces; hence there is more need for knowledge and information for coordinating activities across IPTs.

From Equation 3, the density ( $d$ ) of a directed network is defined as the ratio of the number of observed ties ( $m$ ) among network nodes ( $n$ ) and the maximum possible number of ties among the nodes ( $n(n-1)$ ) (Newman, 2003). The higher the amount of coordination (i.e. number of ties -  $m$ ) with other IPTs, the higher the network density.

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interdependence and tacitness to the nomenclature. He called know-what and know-how that is interdependent and/or tacit complex knowledge, and most suitable for transfer in strong ties.

$$d = \frac{m}{n(n-1)} \quad \text{Equation 3}$$

This leads us to hypotheses 4 and 5 below

*Hypothesis 4: The development of radical or architectural innovation is positively correlated with high inter-IPT network density*

*Hypothesis 5: The development of incremental or modular innovation is NOT positively correlated with high inter-IPT network density*

However, Walker, Kogut and Shan (1997) pointed out that dense relationships have the potential to drown out experimentation and learning, and Ahuja and Lampert (2001) argued that too much density could lead to information overload and confusion. Such scenarios are unlikely to arise in engineering systems IPT networks because IPTs are more likely to under-communicate than over-communicate with other IPTs. Though the monetary cost of communication is decreasing with new technology, communication is expensive in terms of time (Arrow, 1975), and that tends to reduce the propensity to over-interact. Additionally, the propensity to over-interact is reduced by the fact that some IPTs are not collocated. In some cases, IPTs are in different continents.

### **Conclusion**

In this chapter I did a short literature review on interorganizational networks and innovation, and social networks and innovation as departure points for deriving my hypotheses. I found that most literature simply treated innovation as an output. The literature neither considered the different types of innovation nor did it consider innovation as a process. As a result, I developed a set of hypotheses that considered different types of innovation particularly suited to the systems development environment, and considered the different stages of the innovation process as well.

The next chapter describes the procedures for constructing the network of IPTs, measuring innovation and analyzing data for testing the hypotheses derived above.



## Chapter 5: Detailed Research Design

### **Introduction**

This chapter describes the research design for testing the hypotheses derived and described in the previous chapter. I propose using an embedded case study since it allows one to get detailed complete network data. I also describe the procedures for constructing the network of IPTs, and propose measuring innovation using awarded patents, product literature, structured interviews and implemented contributions to employee suggestion programs. Lastly, I will specify the model for testing hypotheses 1, 2 and 3, and describe the analysis for testing hypotheses 4 and 5.

The chapter is broken down into four sections. The first section outlines the advantages of using an embedded case study as the general research approach in this particular context. The second section describes how to construct the network of IPTs based on the flow of technical information, in the event that I do not get access to archival data such as an email database. Section three details the applicability of patents, product literature, structured interviews and employee suggestion programs as measures of innovation in the networked product development context. Finally section four describes the full model for testing hypotheses 1, 2 and 3, and also describes the analysis for testing hypotheses 4 and 5. I provide and critique examples of methods used by other researchers in each section.

### **Embedded case study research approach**

In order to make the contributions described in the previous chapter, I intend to do an embedded case study (Yin, 1984). That is I will gather quantitative data on several units of analysis (both IPTs and innovations) in the context of a single modular design enterprise. The numerous IPTs and innovations, and their context expressed in network metrics allows for a detailed quantitative analysis in the qualitative context of the study.

### Advantages of the embedded case study approach

The embedded case study approach has several advantages in this particular research:

- An embedded case study allows for comparability and consistency among IPTs since the IPTs belong to the same design enterprise but not the same organization in the traditional sense of the word. As stated in chapter one, it is usual to find that some IPTs do not belong to the lead contractor<sup>18</sup>. However, all IPTs share an identity around the complex engineering system that they are all developing.
- One case study ensures the availability of data detailed enough to accomplish the analysis proposed above. Most of the data used in interorganizational studies is obtained from trade journals and industry databases (e.g. Ahuja, 2000; Zaheer et al., 2005) and interviews with one or two interviewees from each organization (e.g. Salman & Saives, 2005). Information obtained from such methodologies is not detailed enough for an analysis of different innovation subprocesses and different types of innovation.
- Additionally, innovation is developed or generated by lower level technical staff and first line supervisors (Aiken, Bacharach, & French, 1980). Thus interviewing staff in the high echelons of the organization who are far removed from the technology case of the firm does not help with analysis of technological innovation. A detailed embedded case study allows access to the technical lower level staff without the expenditure of exorbitant amounts of resources.

#### Disadvantages of the embedded case study approach

The embedded case study has disadvantages as well:

- Generalizability of results might be difficult, since details are true to that one particular setting. Becker (1998) argues for using concepts for empirical generalization. However, the generalization challenge remains concrete in embedded case study research.

#### **Constructing the network**

Since there are many types of interactions among actors (sociological term for nodes in the network - integrated product teams in this particular case), researchers often have to be very specific on the type of interactions that are most informative for their research.

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<sup>18</sup> The lead contractor is the main firm under contract to develop the engineering system. Lead contractors often contract the design/development of smaller parts of the engineering system to other companies

That is, “sound conceptualization...about the theoretical definition of ties...must precede measurement” (Marsden, 1990; pp. 437). In this particular case, I am interested in technical communication (Allen, 1997) during the system development phase. Allen (1997) defines technical communication as comprising of “communication to coordinate work, communication to maintain staff knowledge of new developments in their areas of specialization, and communication to promote creativity” (pp. 2). I am particularly interested in “communication to coordinate work.” However, communication to coordinate work can involve an extremely large number of people; hence I will emphasize a design relationship during the development phase in order to bound the network. In my earlier site visits, I found that this type of communication was predominantly used for problem solving and coordination purposes by engineers who developed the PW4098 engine.

Once the type of interaction is specified, researchers often use the roster method to construct the network among actors (or individuals representing the actor such as the IPT leader). In this methodology, an actor is presented with a roster of all actors in an organization and asked to indicate the actors that she interacted with during the period under study. A compilation of the data from all the actors results in the network or matrix of interactions (e.g. Batallas et al., 2004; Hansen, 1999). In one variation of this method where the actors are not known or where the list of actors is too long for one to remember whom they interacted with, the respondent is often asked to *recall* names of actors that she interacted with (Wasserman & Faust, 1994). Similarly, a compilation of responses results in a network of interactions among the actors. However, the two methods are not mutually exclusive hence some researchers combine both methodologies where the number of actors is reasonably large (e.g. Reagans, Zuckerman, & McEvily, 2004).

Roster and free recall methods suffer from the major drawback that people often forget whom they interacted with after a given amount of time (Allen, 1977). Subsequently the roster / free recall network has lower density than would be the case if all interactions were recorded (Allen, 1977). Additionally, the roster / free recall network tend to be biased towards strong ties (Reagans et al., 2004). This bias could be viewed as filtering

out of less important interactions. Thus the applicability of the two methods depends on the purpose of the research and / or the amount of time that has lapsed between the interaction events and the data gathering.

In order to circumvent the limitations of the roster (also known as the after-thought sampling) method, Allen (1977) and Tushman et al.(1980) used a time-sampling method in which they asked engineers whom they had communicated with at the end of a randomly chosen day. This methodology is grounded in the idea that people are likely to remember whom they interacted with during that one particular day. Nonetheless, time-sampling only works where a project is current. As a result researchers often use archival data such as memos, emails and meeting minutes to supplement the roster and free recall methods (Marsden, 1990; Wasserman et al., 1994). Archival data is also advantageous in the sense that it is less likely to react to the interests of the respondent, and it can be cheaper than sociometric roster methodologies (Burt & Lin, 1977). However, the use of archival data depends on its availability.

Researchers use several other methods to cross validate responses from roster / free recall networks. Some interview multiple team members (e.g. the IPT leader and his/her deputy). For instance, McCord and Eppinger (1993), interviewed product release engineers<sup>19</sup> and their managers. The results from the two interviews are more likely to be consistent if the respondents are subject to the same pattern of relationships, and one way to do that is to interview people at the same organizational level (Marsden, 1990). In a study of inter-divisional technical/market-related information transfer, Hansen (1999) used yet another method to cross validate the responses. He asked his respondents who they *went* to for technical/market-related information, and verified the data by asking who *came* to them for similar information (i.e. reciprocated reports). Hammer (1985) showed that these reciprocated reports are much more likely to match observed ties. In either case, people are more likely to recall routine, typical network ties hence there is less bias in strong ties than in weak ties (Freeman & Romney, 1987; Hammer, 1985).

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<sup>19</sup> Each product release engineer was responsible for each team's technical component (McCord and Eppinger pp. 32)

Depending on the research, researchers also have to establish the strength of the ties among the actors. As discussed earlier, the strength of a tie is often proportional to frequency of interaction between the two actors over a given amount of time. For instance Reagans and Zuckerman (2001) defined the strength of a tie as the frequency of communication between team members in a research team (p. 507). Due to the specialized nature of my research question, I will operationalize the strength of a tie using the same definition as Sosa, Eppinger and Rowles (2004). They defined the strength of a tie as a combination of the criticality of the design information for the functionality of the engine and the frequency of interaction (see Rowles, 1999 pp. 49-50 for details).

In order to construct the network particular to this research, I am going to start by asking for an email database or other archival data that the company might have. A database of emails is the advantageous because it provides time series data and the measures of tie strength are more precise as email counts over a certain period of time.

The second option is to find an ongoing project nearing completion, and ask team leaders to fill out a short web survey on who they interacted with on that randomly chosen day. This time sampling as used by Allen (1977), Tushman et al (1980) and others.

If I neither get access to the email database nor find an ongoing project where I can use the time sampling methodology, I will create a survey instrument fashioned after (Rowles, 1999; pp. 94-96)<sup>20</sup>, (Hansen, 1999; p. 111) and several others whose work has been reviewed in this thesis. Rowles' and Hansen's instruments seem more applicable to my research because they were created and used in complex system development environments.

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<sup>20</sup> The Rowles instrument was used to get data for several publications by Eppinger and Sosa. Rowles and Sosa were Eppinger's students when they designed the instrument and collected the data. Rowles was studying for his SDM masters degree as he was employed at Pratt and Whitney, while Sosa was a PhD student.

### **Testing the hypotheses**

The hypotheses call for measuring both process and product innovation, control variables, explanatory variables and structured interviews for identifying the types of innovation and the innovation phases. I will describe the approaches to these measures in this thesis, but save the actual survey instrument for future research plans.

### **Measuring innovation**

Since companies have different innovating practices, previous researchers have spent some time at the host company learning how that particular company does its innovation. In this particular research, such an exercise will help determine the “amount” of process and product innovation done by the IPTs compared to R&D teams.

Once there is a good understanding of the context, I have to figure the most appropriate measure of innovation. In choosing the measure, it is important to keep in mind that the unit of analysis in hypotheses 1, 2 and 3 is the integrated product team, and the unit of analysis in hypotheses 4 and 5 is the innovation itself. Several measures of innovation are applicable at the IPT level, and they can broadly be classified into input, processing or output measures of innovation. Since I am primarily interested in measuring innovation outputs of integrated product teams, I will focus on measures associated with the output side of innovation.

Predominant output measures of innovation include patents, bibliometrics, literature based innovation counts and expert opinion-based methodologies such as scores on a Likert scale or Q-sort. Unlike the pharmaceutical or chemicals industry, patenting in the aerospace industry is limited (Jaffe & Trajtenberg, 2002; Mueller, 1966). In general companies tend to rely on patents to protect their technological investments, but patents do not offer much protection in the aerospace industry. The technology is usually complex enough to keep competition at bay provided the technical intricacies are kept secret. Thus, patenting would only give competition the opportunity to reverse engineer

the innovation. However, aerospace companies do apply for some patents<sup>21</sup>; hence I will use granted patents as one of the innovation measures. Patent counts tend to be biased towards product innovation because the propensity to patent *process* innovation is less than that of product innovation (Arundel & Kabla, 1998; Griliches, 1990).

There are a few publications on innovations in the aerospace industry hence I will use Literature-Based Innovation Output Indicators (LBIOI) (Coombs, Narandren, & Richards, 1996) as measures of innovation as well. The publications are more product literature aimed at airlines as prospective customers than academic discourse. However, by combing through the product literature for descriptions and mentions of innovations, I hope to come up with another list of innovations. Just like the patents, LBIOI are biased towards under representing process innovation as well.

Since I am also interested in the history of each product innovation for hypotheses 4 and 5, Q-sort and Likert scale<sup>22</sup> based expert opinions are less ideal for measuring innovation in this context. Bibliometrics are better suited for determining the value of an innovation than measuring innovation per se (Godin, 1996). Thus I will adopt patents and LBIOIs, and results from structured interviews as the primary measures of product innovation.

I intend to put the spotlight on process innovation output by interviewing knowledgeable respondents. Such a methodology has been applied in several studies before. For instance, in a study of the informal trade of know-how among rival steel minimill firms, von Hippel (1988) asked his respondents for “concrete examples of process ...improvements that they developed” (p. 79). He verified the responses by interviewing a second set of respondents. Similarly, in a study of the transfer of technology among small firms, Allen, Hyman, and Pinckney (1983) tasked the manager to “think back over the last several years, and tell [them] what he thought was the most significant change in either product or process, that had occurred within the firm” (p. 200). Thus by asking for specific examples and interviewing two people per IPT, I can improve the data validity.

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<sup>21</sup> A quick USPTO search for “United Technologies” - Pratt and Whitney’s parent company – yielded 5406 patents. Some of these patents are obviously awarded to other companies within United Technologies.

<sup>22</sup> e.g. “can you score the innovativeness of this IPT” on a scale ranging from 1 to 7

With the dominance of Lean<sup>23</sup> thinking in the aerospace industry (Murman et al., 2002), each team's *implemented* contributions to the Employee Suggestion Program is another good measure of process innovation (Llyod, 1999; Townsend, 2004). Suggestion programs are particularly useful because they are usually focused on process innovations at the shop floor level, where most of the process innovations go by unnoticed.

Thus I will adopt the methodology used by von Hippel (1988) and by Allen et al. (1983), and counts of each IPT's implemented suggestions from the Employee Suggestion Program as the primary measures of process innovation. Though patents and LBIOIs are biased in favor of product innovation, I will consider any process innovations that the measures yield.

### **Hypotheses 1, 2 and 3: model specification**

Since hypothesis 3 implies a reciprocal influence between innovation and the degree of each node, I will use a two-stage least squares regression to test these three hypotheses.

#### Dependent variable

The dependent variable is the number of unique innovations obtained from the measures described above. Both patented innovations and innovations from product literature have to be assigned to a particular IPT since patents are assigned to the company. I will assign each innovation to an IPT based on the description of the innovation, and check the assignments with a knowledgeable person within the IPT. I will use a similar methodology to assign Employee Suggestion Program innovations to IPTs as well. The interview based innovations would be IPT-grounded based on the IPT membership of the interviewee.

#### Control variables

*IPT experience* - The amount of IPT process or product innovation output is likely to depend on several IPT attributes. I intend to capture some of the key attributes using an

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<sup>23</sup> A process-focused view of the enterprise that is based on the Toyota Production System, with an emphasis on elimination of waste while creating value



averaged 'product development experience within the firm' of each member of the IPT. Experience has the advantage of capturing both technical knowledge and social knowledge of IPT members (Hitt, Leonard, Katsuhiko, & Rahul, 2001). I expect *IPT experience* to have a positive coefficient.

*IPT size* - The amount of process or product innovation is also likely to be a function of the size of the integrated product team hence I will control for IPT size as exemplified by Reagans et al (2001). The size of the IPT is easily measured by the number of team members; I expect *IPT size* to have a positive coefficient.

*Company/supplier dummy variable* – since some IPTs do not belong to the lead integrator, I will have a dummy variable associated with each company involved with a design relationship during the development.

*Technology redesign* – the amount of innovation generated by each IPT could be influenced by the amount of technological redesign that the IPT had to do i.e. compared to a previous engine, how much did the IPT have to change its technical artifact in order to suit the current functional requirements. IPTs that have higher amounts of redesign are likely to be associated with more innovation. In measuring this variable, past researchers have often asked the IPT leader to estimate the percentage of redesign associated with the technology artifact that their IPT was designing (Rowles, 1999).

*Technology readiness level* – For technologies partially developed in R&D labs or advanced technology programs, TRL of the component incorporated into the product is likely to determine the amount of innovation generated by a particular IPT. Companies normally have TRL measures, and I intend to use those measures.

#### Explanatory/Independent variables

*Number of structural holes* – The number of structural holes spanned by a node's linkages is indicated by the effective network size (Burt, 1992). The higher the effective network, the higher the number of structural holes spanned by the links associated with each node. Note that these are structural holes spanned by both strong and weak ties.

*Number of strong ties* – A simple count of the strong in-degree. I am using the in-degree in this hypotheses because the in-links are “expensive” compared to the out-degree because the in-degree are limited by bounded rationality. Additionally, I am interested in in-directed links that can help an IPT generate process innovation.

*Innovation weighted in-degree ( $I_w$ )*– a sum of the products of each node’s tie strength ( $\hat{S}$ ), tie weight ( $\hat{W}$ ) and the amount of innovation of the alter ( $\check{I}$ ). This variable captures the influence of the innovativeness of the alter on the ego.

$$I_w = \sum^n \hat{S} \times \hat{W} \times \check{I} \quad \text{Equation 4}$$

$\hat{S}$  – either 1 or 2 depending on the tie strength

$\hat{W}$  – the weight of the tie which is the inverse of the geodesic distance of each tie from the ego. The geodesic distance between two nodes is the shortest number of links between any two nodes. Thus the weight of a direct tie is 1, that of a tie removed by one tie is ½ etc

$\check{I}$  – sum of an alter’s product and process innovations

$n$  – the number of nodes in each node’s cluster. The cluster of a node consists of all other nodes that are tied to the node under consideration.

### Hypothesis 1

*Hypothesis 1: Given similar effective networks, IPTs with more in-directed strong ties will have more process innovation than IPTs with fewer in-directed strong ties*

This hypothesis is tested with only *process* innovation counts as the dependent variable since it is particular to process innovation, and the hypothesis is supported by a statistically valid positive coefficient of “number of strong ties”

## Hypothesis 2

*Hypothesis 2: Given similar access to structural holes, and similar number of strong ties, IPTs linked to IPTs with more process innovation will have more process innovation than IPTs linked to IPTs with less process innovation.*

Similar to hypothesis 1, Hypothesis 2 is tested with process innovations only as the dependent variable, and it is supported by a positive and statistically valid coefficient of “innovation weighted in-degree”

## Hypothesis 3

*Hypothesis 3: An IPT's amount of both process and product innovation explains the IPT's degree (i.e. the amount of innovation associated with an IPT induces the amount of its links.)*

Dependent variable - For this hypothesis the degree (both strong and weak) of a node is the dependent variable.

Explanatory variables – both *product and process innovation* counts

Control variables - the *IPT size* and *Technology redesign, Technology readiness level*

## **Hypotheses 4 and 5**

*Hypothesis 4: The development of radical or architectural innovation is positively correlated with high inter-IPT network density*

*Hypothesis 5: The development of incremental or modular innovation is NOT positively correlated with high inter-IPT network density*

From the IPT point of view, hypotheses four and five are global in nature because they investigate the impact of the entire network density on technological innovation. Ordinarily testing this hypothesis would involve constructing several networks, and running a regression of innovation output on the network density. However, I get the opportunity to contribute by using each technological innovation as a unit of analysis and

analyzing the history of the development stage of each technological innovation from those who had first hand experience or are knowledgeable about the development of the innovation.

This approach has been applied by other researchers before. For instance, Obstfeld (2005) used a related methodology when he investigated the impact of the density of social ties and diversity of social ties on organizational innovation. He did an ethnographic study supplemented with two surveys; one for constructing the social network and the other on people's innovation involvement. Similarly, Riggs and von Hippel (1994) traced the history of each of 64 "recent" innovations from Auger and Esca in the scientific instruments industry in order to investigate the link between incentives to innovate and the functional source of the innovation.

#### Proposed analysis

The first stage of the analysis gathers the product innovations identified using the methodologies above. The innovations are then classified based on the Henderson and Clark (1990) framework (see chapter 2) by asking whether each innovation changed the core-concept or interfaces of the technical artifact that the IPT developed.

The second stage investigates the impact of an innovation on density. The density ( $d$ ) of a directed network is defined as the ratio of the number of observed ties ( $m$ ) among network nodes ( $n$ ) and the maximum possible number of ties among the nodes ( $n(n-1)$ ). The formula for calculating the density of a directed network is shown in Equation 5. For example the density of a directed network with 4 nodes and 5 ties is  $5/(4 \times 3)$ .

$$d = \frac{m}{n(n-1)} \quad \text{Equation 5}$$

By asking the respondents if other IPTs within the network got involved during the development phase of the innovation, I get a sense of whether density increased or did not during the development of an innovation. If more IPTs from the same network got involved (i.e.  $m$  increased), then the density increased for that particular technological innovation. Analysis of the innovations that led to an increase in network density and

those that did not will help test hypothesis 4 and 5. Hypotheses 4 and 5 imply that radical/incremental innovations will be associated with an increase in other IPTs involvement, while incremental/modular will not.

### **Conclusion**

In this chapter, I proposed using an embedded case study with detailed quantitative data on IPTs and their innovations as the overall research methodology for testing the hypotheses derived in chapter four. I described the methodology for constructing the network of IPTs using structured interviews, in the case that I do not get access to an email database. In measuring innovation, I argued for using patents, product literature, employee suggestions programs and structured interviews. Lastly, the chapter outlined the model for testing hypotheses 1, 2 and 3, and detailed the analysis for testing hypotheses 4 and 5.

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## Appendix A

### PW4000 -112” engine Series

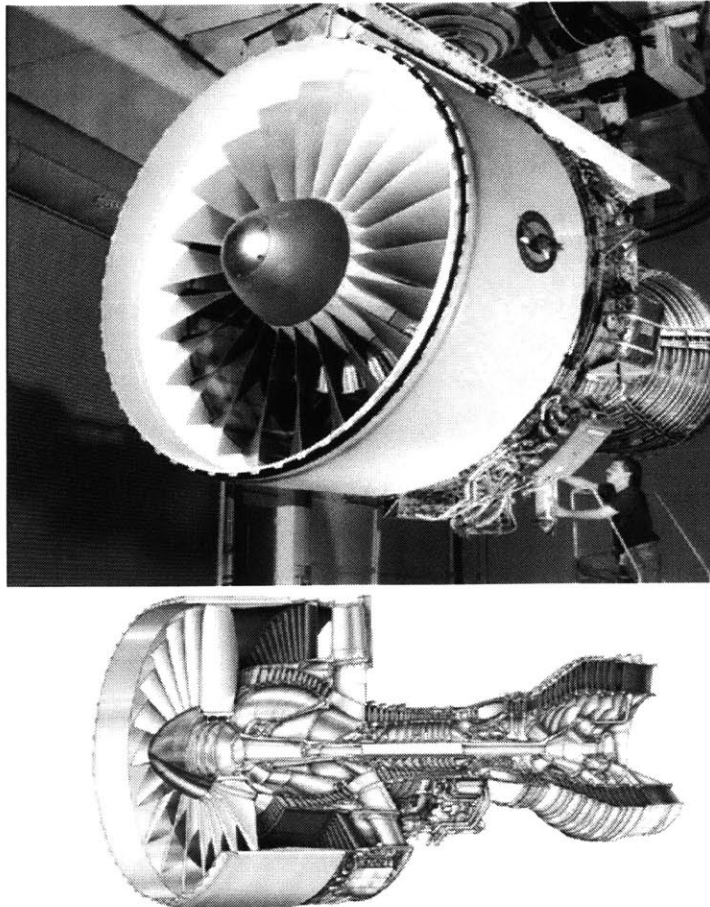


Figure A.1: Two images of the PW4000-112”. Image at the bottom is the cutaway of the engine.<sup>24</sup>

Development of the 112” engines started in 1990 and the first engine was developed for Boeing 777. 112” engines are particularly famous for their high thrust. Key innovations associated with the first of the 112” (PW4084) included the new shroudless hollow titanium blades, redesigned HPC case whose design was exported back to the PW4000-94” when it ran into problems, six stage LPC and a seven stage LPT. The PW4090 that followed the PW4084 had improved HPC dynamics, bowed stators that reduced diffusion and blade roots that reduced flow separation. In general these engines were highly fuel efficient and had high resistance to foreign objects.

<sup>24</sup> Source: Pratt and Whitney [http://www.pratt-whitney.com/news\\_presskit\\_images.asp](http://www.pratt-whitney.com/news_presskit_images.asp)

The No 2 carbon seal failed on the PW4090 but that was quickly fixed by changing to wet-face running against an oil film (Janes 2000). The PW4098 had more challenges. Certification was postponed thrice, first because of cracked stators and in flight compressor rubs, and then because of “sudden fuel chops” (Janes pp. 612). These PW4098 problems went on to affect the development of the PW40102. Nevertheless, the PW40102 was later developed to be one of the most powerful engines in the industry. Table A.2 summarizes characteristics and milestones of the 112” engine series.

<b>PW4000-112" Engine Characteristics</b>		<b>Program Milestones</b>
Fan tip diameter	112 inches	October 1990 - Program launch
Length, flange to flange	191.7 inches	November 1993 - First flight
Takeoff thrust	74,000 - 98,000 pounds	April 1994 - FAA engine certification
Flat rated temperature	86 degrees F	May 1995 - 180-minute ETOPS approval
Bypass ratio	5.8-to-1 to 6.4-to-1	June 1995 - Entry into service
Overall pressure ratio	34.2 - 42.8	
Fan pressure ratio	1.70 - 1.80	

Table A.2: Summary of PW4000-100 key characteristics and milestones<sup>25</sup>

<sup>25</sup> Pratt and Whitney [http://www.pratt-whitney.com/presskit/factsheets/commercial\\_2003\\_pw4000\\_100.doc](http://www.pratt-whitney.com/presskit/factsheets/commercial_2003_pw4000_100.doc)