Hierarchy in Industry Architecture: Transaction Strategy under Technological Constraints

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ABSTRACT

Motivation -- Industrial firms survive, sustain and co-evolve by participating in the sector of innovation and production through industrial transactions with each other. However, it is difficult for specialized firms to be aware of and manage accordingly the kind of systemic constraints and opportunities induced by relevant but indirect transactions, as well as the technological and economic requirements of their value chains, which they cannot control or even sufficiently observe. The myopia may cause specialized firms to implement incorrect strategies, leave them vulnerable to system failures or ignorant of emerging opportunities. This implies a paradox: the simultaneous needs to specialize and to understand and manage the big picture of the eco-system.

Goal -- Previous industry studies have focused on the question if a transaction with an external firm is needed rather than in-house production, and on empirical work from single industries or bilateral relationships between firms. Meanwhile, the firms' positions in the sectoral transactional network are also influential to the success and performance of firms. In this dissertation, I conduct transactional network analysis to explore how firms are organized in the sector of aggregated industries, in order to shed light on the set of previously ignored knowledge on industrial transactions, which is valuable to single firms in designing strategies and managing operations but is not available from firm- and industry-level analysis.

Hierarchy in Industry Architecture -- At the sector level, existing theories often assumed hierarchical or non-hierarchical relationships among industrial firms, and quantitative evidence on variable degrees of hierarchy in industry sectors is lacking. This dissertation first identifies and defines the type of hierarchy relevant to industry studies - *flow hierarchy*, develops a network-based metric on the degree of hierarchy (one-way flow of transactions), and applies it to the transaction data from two industrial sectors in Japan. The empirical results show that the electronics sector exhibits a significantly lower degree of hierarchy than the automotive sector due to the presence of many transaction cycles. It shows that the simplistic hierarchy hypothesis for production sectors does not always hold.

Industrial Network Model and Transaction Specificity -- I further create a *network simulation model* with random networks to relate sector-level hierarchy degrees to firm-level behavioral variables, and infer *transaction specificity*, i.e. the extent to which a firm is captive to a niche of customers positioned closely in the industrial network hierarchy. The model

builds on three basic rules on market structures, i.e. hierarchy, niche, and the mapping relationship between roles and positions. Transaction specificity provides a way to quantify the tendency of a firm to fix or institutionalize its role according to its relative network position, or where the transactions of a firm are oriented in the value chains, whereas traditional studies analyze whether a transaction versus in-house production is needed. The result shows that transaction specificity in the electronics sector is quantitatively much lower than that in the automotive sector.

Interviews and Firm Boundary Strategies -- I further conducted interviews with nine firms in the two sectors and found that, with decision rationales related to product modularity, innovation dynamics and asset specificity, the major electronics firms take the *permeable vertical boundary strategy* and *diversified horizontal boundary strategy*, which decrease transaction specificity so that many transaction cycles emerge in the electronics sector. My analysis shows *the permeability of a firm's vertical boundary*, i.e. playing multiple value chain roles, is the necessary condition for transaction cycles to emerge. Meanwhile, these two strategies are not feasible in the automotive sector according to interviews. They are also not observed in the American electronics sector. My data show the American electronics firms tend to be vertically specialized in the value chains.

Social-Technical Arguments -- Linking network analysis results, interview data, and the prior work on the physical limits to product modularity, I argue that *higher power level of a sector's technologies leads to higher transaction specificity, and more hierarchical transaction flows across the sector*. High power technologies constrain strategic transaction choices, while lower power technologies enable a larger option space of transaction strategies, for companies to explore and exploit.

Implications -- For academics, the use of network analysis permits transaction cost analysis, or more general analysis of transaction-related decisions, to be extended from the boundary of a firm to the architecture of a sector comprising related industries. It gives us a bird's-eye view to observe firm-level transaction behaviors and create new knowledge on transaction specificity. In addition, the analysis of the physical properties of product technologies allows us to interpret the difference in transaction specificities and hierarchy degrees of different sectors, which economic and sociology theories cannot explain.

For industry practitioners, this research suggests that firms' choices for industrial transactions are under some predictable constraints from product technologies. A better understanding of the linkages between industry architecture, firm transaction strategy, and product technology, in turn can guide companies to tailor transaction strategies to implicit technological constraints and to adequately explore strategic options made feasible by technologies.

Thesis Supervisor: Christopher L. Magee
Committee Members: Daniel E. Whitney, Carliss Y. Baldwin, Daniel Roos

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This thesis is a temporary departure from my home country, China, and the automotive industry that I have always cared about. As a matter of fact, by learning to see from outside the "boxes" I used to be in, I find myself better able to explain many puzzles that frustrated me when I was an automotive engineer in China. I feel fortunate and satisfied about my journey at MIT. Being at MIT, I have gained opportunities to go beyond my country and myself, to travel to the U.K., Japan, Switzerland, and elsewhere, to work with researchers around the world, to study different industries in different countries, and to study economics, management, policy, sociology, beyond engineering. For me, doing my PhD at MIT has been a process of inquiring about and finding the real meaning of life. It has not only made me understand myself better and improve myself, but has also shown me what I should do in the rest of my life, a meaningful life, to help others and my family, to make a positive impact in my country and the world. In particular, I am proud of being part of the venture of developing the emerging field of engineering systems at MIT, and enjoy making my contribution. I am a faithful believer in the potential impact of engineering systems education and research, and I will continue to serve as a missionary of the engineering systems ideas wherever I may be in the future. Thanks to MIT. Thanks to ESD.

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谢谢你们，爸爸妈妈。没有你们的爱，我什么也成就不了。没有你们的爱，任何成就都没有意义。

Terms and Definitions

Hierarchy – a generic structure, in which levels are asymmetrically ranked according to a specific type of relation.

Containment Hierarchy (Network) – in containment hierarchy, entities are divided into groups that are further divided into subgroups and so on over multiple levels. A containment hierarchy is similar to the concepts of “nested hierarchy” and “inclusion hierarchy”.

Flow Hierarchy (Network) – in flow hierarchy, the order of levels is essentially determined by the direction of the flows of necessary resources through the network. Via being connected by such flows, the entities co-evolve and may self-organize into a flow hierarchy. In an industrial network of firms, flow hierarchy arises when there is unidirectional movement of materials, components, or parts through a series of value-adding stages, and payments in a reverse direction. Cycles violate flow hierarchy.

Industry Sector – a network of firms in different but related industries that supply complementary goods for making a coherent set of system products.

Industry Architecture – the pattern of transactional relationships between all the firms in a sector comprising several levels of industries.

Transaction Specificity – the degree to which a firm is captive to a specific niche of customers positioned closely in the industrial network hierarchy.

Transaction Breadth – the average number of transactional relationships per firm in a sector.

Boundary of Firm – It is where a firm’s transaction activities take place. Firm boundaries are the demarcation between a firm and its environment, and they are where the two interact. This thesis considers different kinds of boundaries of a firm, including vertical boundary, downstream horizontal boundary and upstream horizontal boundary (details in Chapter 5).

Technology – Technology is a set of techniques, tools, or processes which turn knowledge, ideas or principles into practical value for certain purposes.

Technology Regime – the technological environment of a sector, in which firms’ innovation, learning, and production activities take place. It imposes technological requirements on firm behaviors.

Chapter 1

Introduction: Industry Architecture

"The significant problems we face cannot be solved at the same level of thinking we were at when we created them."

-- Albert Einstein

1.1 Motivation

The competitive economic climate demands that firms improve their efficiency by specialization on one hand, and on the other dynamically engage in the network of complementary and competing firms on their value chains in order to optimize their uses of their own capacity and capabilities. Nowadays, very few companies succeed in managing an entire value chain in house in a way that is competitively efficient and effective in the marketplace.

That is why industrial firms buy inputs and sell outputs via firm boundaries. Firms survive and sustain by participating in the larger economic system (e.g., value chains, or value networks) and by co-evolving through their transactions with each other. For example, an industrial company, like Sony or Intel, procures many intermediate products (e.g., components and parts) from and sells many intermediate products to other such companies, in addition to dealing directly with end-use consumers. Strategic transaction choices, such as what a firm procures, who it procures from, what it sells, and who it sells to, are fundamentally important. Such strategic choices on industrial transactions determine the firms' positions in the larger eco-system or value network, which are influential to the success and performance of firms. However, many assumptions and constraints affect these strategic choices, and the managers who design the strategies may or may not be fully aware of those factors.

It is important for industrial firms that are economically connected to each other to understand systematically the constraints on and strategic possibilities for industrial transactions, which are imposed by their participation in value co-creation networks. This dissertation aims to develop new knowledge and new theories about some previously ignored aspects of industrial transactions.

For specialized firms, it is particularly difficult to be aware of and manage accordingly the kind of systemic constraints and opportunities induced by the relevant but indirect transactions, as well as the technological and economic requirements of their entire value network, which they cannot control or even sufficiently observe. This myopia may cause specialized firms to implement incorrect strategies, and it may leave them vulnerable to system failures or ignorant of emerging opportunities. This implies a paradox: the simultaneous needs to specialize and to see and manage the big picture.

This paradox invites exploration of the architectures and dynamics of the larger ecosystem in order to shed light on the set of knowledge, which can be valuable to single firms in designing strategies and managing operations but is not available from firm- and industry-level analysis of firms. Recognizing the need to change the level of analysis resonates with Albert Einstein's philosophy of scientific exploration, *"the significant problems we face cannot be solved at the same level of thinking we were at when we created them"*.

This motivation in fact has guided the strategic planning and evolution of my doctoral research. My ultimate purpose is to develop new knowledge to help single firms better design and manage industrial transactions. But my research started with analyzing the architecture of the entire network of firms connected by transactional relationships in a sector of aggregated industries. I believed and expected that new understanding of the big picture (e.g., industry sector) and the relative positions of firms in the sector would lead to new understanding of the decisions and behaviors of single firms. Essentially, the big picture is the collective result of the behaviors of individual firms. Therefore, I hypothesize that relative positions of firms to each other in the sectoral network may convey some fundamental information about firm behaviors and strategies that we would not learn when focusing the analysis at the firm level.

In a nutshell, this dissertation aims to develop new understanding of and deliver new insights into the strategic transaction choices of single firms by analyzing how they are organized at the sector level according to their transactional relationships.

1.2 Unit of Analysis: Industry Sector

1.2.1 Traditional Studies on Industrial Transactions

Previous studies interested in industrial transactions have investigated industry structures in terms of vertical integration and dis-integration (Nishiguchi, 1994; Fine, 1998; Sturgeon, 2002; Jacobides, 2005; Nagaoka, Takeishi and Norob, 2008), horizontal concentration versus diversification within a single layer or industry (Penrose, 1959; Chandler, 1962; Teece, 1982; Teece, Rumelt, Dosi and Sidney, 1994; Davis and Duhaime, 1992; Nobeoka, 1996), and changes within such conceptual frameworks. Studies of the structure of a single industry often investigate the horizontal divisions of labor, revenue, or assets by firm, firm type, or region, in a single-layer industry. Neoclassical microeconomic theories of the economies of scale and scope are often the basis of analysis. Studies of vertical integration focus on the division of labor between two groups—customer and supplier—and such studies are most often based in transaction cost economics (Williamson, 1975; 1981; 1985).

In general, traditional studies of industrial transactions focus on the dyadic relationships between suppliers and customers, or on a single industry layer, but do not address multiple layers of suppliers and customers, or the possibility that numerous complementary goods will be combined into large systems. We have not learned much about how industrial transactions are embedded in the larger ecosystem, which includes multiple related industries on the value chains, up to the system integrators of finished products. The micro analytic emphasis neglects the important fact that the firms across related industries co-evolve. Many of their related economic activities, including innovation, development, and production of end-user products and services, do not happen just between firms within a single stable industry, but throughout the related value chains, or value networks (Jacobides, 2005; Jacobides and Winter, 2005; Christensen and Rosenbloom, 1995). The narrow traditional focus may have left a set of valuable knowledge about industrial transactions unexplored.

1.2.2 Industry Sector

In this dissertation, I take an industry sector, i.e., a group of industry layers, as the level of analysis, rather than a firm, a supplier/customer pair, or an industry. Following Malerba (2002) I use the term “sector” to mean a network of firms in different sub-industries that supply complementary goods for making a set of system products. For example, an automobile sector includes the system integrators, sub-system integrators, component suppliers, and materials suppliers that are involved in the innovation, development and production of automobiles. To avoid confusion, I consider firms in a particular role (such as sub-system integrators) to form an “industry,” and the collection of these industries to be the “sector.” Various types of relationships, such as alliances, joint ventures, and competition, may connect the firms in a sector. Here I investigate transactional relationships—that is, the compensated exchanges of components and parts to be combined for making the final products—because these relationships are necessary for a firm to survive and to be part of an economic system. Sequential or parallel industrial transactions coordinate the intermediate innovation and production activities across firm boundaries, collectively forming industry sectors[1].

Figure 1.1 demonstrates the position of the sector in the nested hierarchy of the units of analysis available to researchers. Traditional management studies take people, tasks, a firm, a transaction, an industry, or a market as the unit of analysis. Traditional engineering studies take components, products, or processes as the unit of analysis in order to better understand technologies, and design, produce and deliver products that meet customer needs. In this thesis, I analyze and compare the patterns of transactional relationships of firms in different industry sectors, and examine the factors related to products, processes, and people that may interact to influence the patterns of inter-firm transactions in different industry sectors.

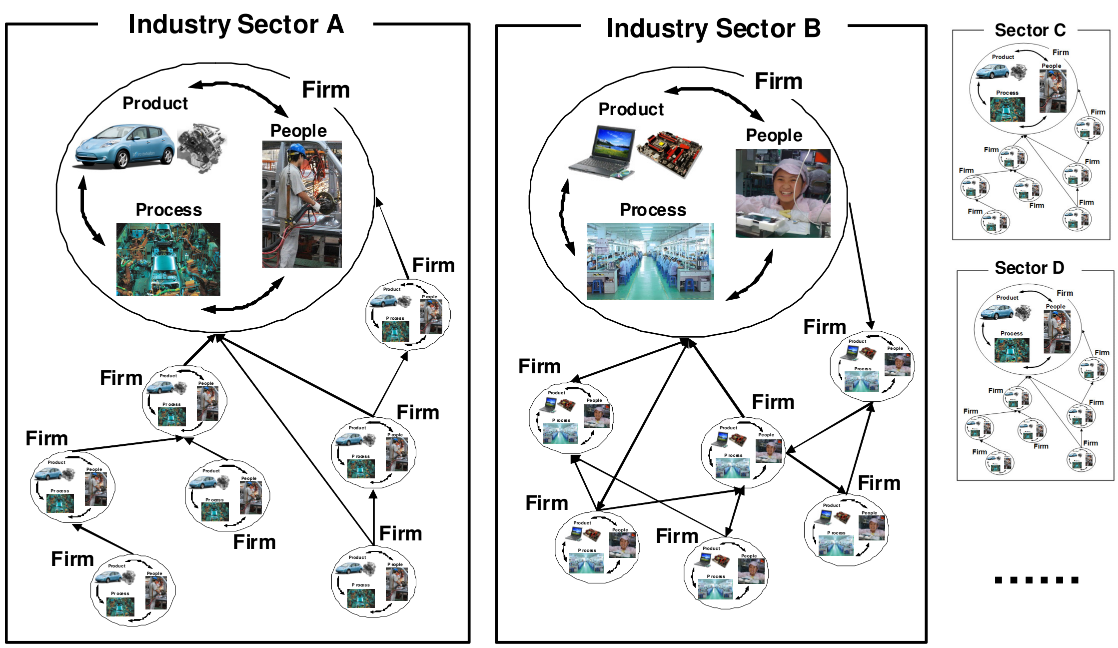

Figure 1.1 Demonstrating the available levels of analysis.

Note: A square represents a sector, a circle indicates a firm, and the arrowed line between a pair of firms represents a supplier-customer relationship. This figure does not present specific real-world sectors.

[1] Obviously, the analysis of an industry sector focuses on firms in the sector and the transactional relationships between them. In contrast, in the analysis of a traditional supply network, inventories or plants and the shipments between them are the interests and focuses of analysis.

By expanding the horizon of analysis to the sector of innovation and production, new questions can be asked, and new knowledge can be expected to emerge. New methods must also be developed to exploit the new level of analysis and to address the need to connect the sector-level analysis to the firm level, which is our ultimate interest. In order to analyze and understand an industry sector, *engineering systems* concepts, theories, and related methods, which aim to understand, design, and manage large-scale complex social-technical systems (e.g., large industry sectors), may be appropriate and instrumental.

1.3 Sector as Engineering System: Concepts and Methods

An *engineering system* is "a system designed or evolved by humans having some purpose; large scale and complex engineering systems which will have a management or social dimension as well as a technical one," according to the MIT Engineering Systems Division's *ESD Terms and Definitions*. A production industry sector is a typical engineering system, where a large number of autonomous humans and organizations compete, complement each other, and co-evolve through dynamic innovation and production activities. Therefore, an industry sector can be best characterized by and investigated using the key concepts in engineering systems analysis: complexity, socio-technical nature, architecture, "ilities[2]", etc.

1.3.1 System Complexities: Largeness, Evolution, and Emergence

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[2] Ilities -- desired properties of systems, such as flexibility or maintainability, often ending in "ility." These

A complex system is "made up of a large number of parts that interact in a non-simple way" (Simon, 1962), so that it is non-trivial to infer or predict the behaviors and properties of the whole system from the properties of the parts and the laws of their interactions. Such properties of systems are often called emergent properties. This was first explained by Nobel laureate in physics Philip Anderson in his famous 1972 paper, "More Is Different."

Complexity may be the most important concept in engineering systems studies, since many engineering systems fit the definition of complex systems. According to *ESD Terms and Definitions* (2002), two types of system complexities are most interesting for engineering systems: behavioral complexity and structural complexity.

> *A system is behaviorally complex if its behavior is difficult to predict, analyze, describe, or manage. In contrast a system is structurally complex if the number of parts is large and the interconnections between its parts are intricate or hard to describe briefly. Systems that are structurally complex are usually behaviorally complex…On the other hand, most behaviorally complex systems are structurally complex as well (ESD Terms and Definition (2002).*

A production industry sector is a typical complex system. First, an industry sector, such as the electronics production sector, is a structurally complex system because it is sufficiently large and is composed of hundreds of firms and thousands of transactional or collaborative relationships among them. For this reason, it is often difficult for a specialized firm in the middle of the value network to understand and manage its relative position in the overall economic network, and to foresee overall industrial environmental changes.
Second, an industry sector is behaviorally complex in that it does not have a central designer

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properties of systems are not necessarily part of the fundamental set of requirements on the system's functions or or architect[3]. Firms compete with and complement each other to co-evolve. The interactions between the firms in a sector may lead to emergent properties and behaviors different than those that the individual firms themselves display.

In addition, the multidimensionality of an industry sector also adds to its overall complexity. In practice, the properties and behaviors of a sector influence and are influenced by their economic, societal and physical contexts, as well.

1.3.2 System Dimensions: Socio-Technical

In socio-technical systems, both human and non-human elements interact, and social or economic dimensions tend to dominate (ESD Symposium Committee, 2002). An industry sector is a typical socio-technical system.

First, a production industry sector has social and economic dimensions. An industry sector is a market where the price mechanism coordinates the transactions and exchanges of components and parts. Firms are connected by transactions that allow them collectively to innovate, develop, and produce a coherent set of products that satisfy a coherent set of human needs. However, an industry sector is different from a pure market, such as the stock market, where traders can buy from and sell to any other traders, or the Tokyo fish market, where the

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performance (ESD Symposium Committee, 2002).

[3] Though some powerful firms in some sectors, such as Toyota in the Japanese automotive sector, seem to impose certain degree of influence to other firms in the same sectors, they are not designers. Toyota is neither a designer of the Japanese automotive sector, nor a designer of the relationship with the suppliers in which it has a stake. Investing in that kind of tight relationship (seemly non-market) is a still a collective result of the profit-seeking strategic choices of both Toyota and its suppliers.

commodity is quasi-uniform and the dominant force is the price mechanism. White (2002) coined the term “production market” to distinguish a production industry sector from a pure market.

Second, a production sector has a technical dimension, indicated by the products of the sector. Essentially, the physical technologies embedded in products that are innovated, produced and transacted in the sector have strong influences on, and are also influenced by, the structure and functions of the sector. The economic activities in different sectors for different products may undergo different technological constraints so that they are organized differently (Malerba and Orsenigo, 1993; 1996; 1997; Castellac, 2007). Industry or market also co-evolves with products and processes in the industry (Fine and Whitney, 1996; Utterback, 1996).

However, an industry sector is not a pure technical system, which is often designed for a purpose. An industry sector is not engineered by anyone, but rather is a system that emerges from the participation and interactions of self-organized firms, coordinated by technical and economic forces.

Coase (1937)'s concept of a “specialized exchange economy” summarizes the technical and market dimensions of an industry sector. In a production sector, if the price mechanism is the invisible hand, technology might be regarded as another, more visible hand. In fact, the inter-play of both “hands” contributes many of the complexities that hinder our understanding of industry sectors. Thus, one cannot straightforwardly apply traditional economic knowledge about firms and organizations or product-level technical knowledge to theories of the industrial sector as a whole. This dissertation aims to holistically integrate knowledge and methodology that engineering, economics, and other social sciences offer, in order to develop new understandings of and theories about industry sectors.

1.3.3 System Description and Analysis: Architecture and Networks

- **System Architecture**

In the words of E. O. Wilson (1998), "the greatest challenge today, not just in cell biology and ecology but in all of science, is the accurate and complete description of complex systems."(Strogatz, 2001). System architecture is a fundamental way to describe such complex systems as an industry sector. According to the *ESD Terms and Definitions* (2002), "the architecture of a complex system is a description of the structure or regularity of the interactions of the elements of that system (inherently the non-random and longer lived aspects of the system relationships)."

Architecture exists in all kinds of systems, such as enterprises, buildings, transportation systems, physical products, etc. Architectures may be designed by a designer, be determined by regulations, or emerge from evolutionary processes. Some simple examples of system architectures are tree, layer, module and hierarchy, etc. Because of architecture's ubiquity, it is an important proxy or abstraction for understanding, designing, and managing complex systems. Architecture is important first because it conveys functions and affects behaviors.

For instance, the architecture of an organization affects the efficiency and effectiveness of the individual members and their interactions. The architecture of a power grid may affect the robustness and resilience of power transmissions (Whitney et al., 2004).

Therefore, architectural knowledge can be used to manage complexity and design systems to behave in desired ways (Simon, 1962). Scholars from different fields have analyzed the architectures of the systems of their respective interests. For example, Henderson and Clark (1990) showed how firms in the semiconductor photolithographic alignment equipment industry gained market leadership by creating and capturing value through a series of innovations in the architectures of products (as opposed to components). Baldwin and Clark (2000) illustrated how the architectural change of personal computers from integral to modular led to the expansive growth of the personal computer markets and the dramatic changes in the architecture of the computer industry sector. Dodds, Watts and Sabel (2003) used an organizational network model to indentify a class of organizational architectures that reduce the likelihood of the congestion-related failure of individuals and improve the robustness of the organization network over a wide range of environments. Such findings provide strategic guidance in designing the architectures of firms for desirable performance.

Since an industry production sector is a complex system by nature, architecture may be a useful proxy for understanding sector-level properties, the firms involved in the sector, and the products that the sector innovates and produces.

- **Networks**

Architecture is a proxy or abstraction of complex systems. Using analysis of architecture to generate new knowledge would require practical methodologies or techniques to produce analyzable representations of the architectures to be studied. Networks-based approaches have shown to be appropriate tools for analyzing the architectures of systems that can be described as inter-related parts and their interactions. A network is a set of items with the connections among them (Newman, 2003).

Network analysis can be a powerful way to understand the architectures of industrial sectors because an industry sector can be interpreted as the firms and the interactive interrelationships among them. The most crucial relationship is the transaction, as it is the reason the firms are gathered together to form the sector and why the sector is economically meaningful. A network model of an industry sector would be built using the firms as nodes and their interactive inter-relationships as the links. In fact, this framing of economic systems as networks is the foundation of economic sociology (e.g. White, 2002) and network economics (e.g. Plott, 2001).

Two strands of network-based techniques are dominant in representing discrete systems: 1) directly visualizing a system as nodes and links among them; 2) Design Structure Matrix, or Dependency Structure Matrix (DSM), which visualizes the system as an adjacency matrix where a non-blank entry in cell (i, j) indicates a link from i to j (Eppinger et al. 1994). Figure 1.2 demonstrates how these two methods represent two example discrete systems. No matter what representations are used, network analysis and manipulation is in fact rooted in graph theory and discrete mathematics. The foci of network analysis often range from the properties of individual nodes, such as centrality and prestige (Wasserman and Faust, 1994), to the overall properties of a network as a whole, such as small world dynamics (Watts and Strogatz, 1998) and power-law degree distribution (Barabasi and Albert, 1999).

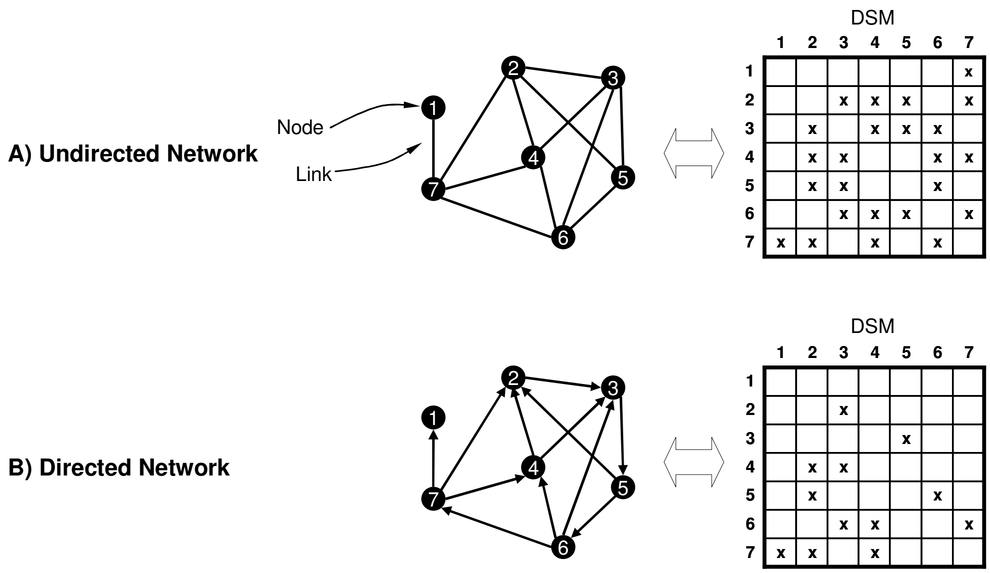

Figure 1.2 Two example networks with seven nodes and twelve links.
Note: Each system is represented by a network and by a matrix (the DSM).

Network analysis has been conducted to study the architectures of a wide range of complex systems in many domains, including engineering (e.g. automobiles, software, the internet), natural sciences (e.g., food webs, neural networks), and social sciences (e.g., social networks) (Strogatz, 2001; Newman, 2003). Networks can be used to represent traditional supply networks, in which the nodes are inventories or plants. In the later chapters of this thesis, industry sectors are to be depicted as the networks of firms as the nodes, and supplier-customers transactional relationships as the links. Nakano and White (2007) have shown that a regional economy around the Tokyo district can be represented as a directed network of firms connected by supplier-customer relationships, and they analyze its architecture using the most popular network analysis metrics and models. The details of my network models for two empirical industry sectors will be given in Chapter 3.

In general, for a network analysis to be meaningful, the techniques used must be suitable to the questions. The network methods and analyses in later chapters of this dissertation are all tied to an upfront puzzle about industry architecture, which I encountered when expanding the level of analysis to a sector.

1.4 Industry Architecture

1.4.1 Definition of Industry Architecture

This dissertation follows Jacobides et al (2006)'s definition of "industry architecture" as the stable but evolving relationships along the value chain; that is, the patterns in which labor and assets in a sector are divided between different types of industry participants, and the associated set of "rules and roles" that emerge (Jacobides, Knudsen, and Augier, 2006)[4]. The notion of industry architecture considers the overall template that describes the distribution of labor and assets among a set of co-specialized firms across a set of industries.

In the analysis of this thesis, industry architecture is more specifically the pattern of transactional relationships between all the firms in a sector comprising several levels of

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[4] "Industry architecture" by Jacobides et al (2006) is in fact the architecture of the interrelated industries in a sector. We have seen other researchers call it sectoral architecture. In this paper, we will simply use "industry architecture".

industries. Thus, the necessary level of analysis for researching industry architectures is the transactional network of firms among the complementary industries in a sector. The analysis of industry architectures may provide opportunities to ask new and important questions about firm behavior and performance, technology dynamics, etc.

There have been an increasing number of studies at the sector level on how the internal boundaries of industries change in a sector (Langlois and Robertson, 1992; Jacobides, Knudsen and Augier, 2006), and on how sectors differ in terms of their technological bases, innovation patterns, economic behavior and performance, and the correlations between these differences (Nelson and Winter, 1982; Dosi, 1988; Malerba and Orsenigo, 1993, 1996; 1997; Jacobides, 2006; Castellacci, 2007). However, our understanding of how sectors differ in terms of their architectures and of the technological and economic mechanisms that cause such differences is still limited.

1.4.2 The Hierarchy Puzzle of Industry Architecture

At the sector level, existing studies often observe or suggest a hierarchical architecture (Coase, 1937; Malerba, 2002; Dalziel, 2007; Nakano and White, 2007), in which production processes are organized into sequential stages (Coase, 1937; Abernathy, Clark and Kantrow, 1983; White, 2002a)[5]. According to Harrison White (2002b:87), "production markets" show "persistent directionality in continuing flows of intermediate goods" in which "only a niche within an industry establishes you in a line of business." Such hierarchy does not exist in a

[5] This is also implied, to some extent, by the hierarchical organization of technological artifacts in the product systems that the sectors innovate and produce (Christensen and Rosenbloom, 1995; Murmann and Frenken,

pure market such as a stock market, where traders can buy from and sell to any other trader.

The recognition that production markets may have hierarchical architectures is a significant difference from the neoclassical institutional economics tradition of assuming total freedom in markets. In Nobel economics laureate Oliver Williamson (1975)'s *Markets and Hierarchy*, the market is assumed to be a non-hierarchical space, because it represents the opposite of the "hierarchy" mechanism for organizing economic activities. Williamson uses the word "hierarchy" to represent enterprises, such as firms, where the span of command and control is available and replaces transactions.

Using network analysis, Nakano and White (2006; 2007) have offered empirical evidence that the network of firms (connected by supplier-customer relationships) in the Tokyo economic district exhibit a strict hierarchical architecture. Based upon this, they assume a simplistic hierarchical view for production networks; that is, they hypothesize that hierarchy is a general property of production markets. They argue that firms in production markets tend to become entrenched in their positions and roles as buyers and sellers over time, so that the architecture of production markets can be assumed to be directional or hierarchical. In contrast, hierarchy does not exist in a pure market such as a stock market because actors there constantly change roles, and therefore an enduring institutionalized role structure does not exist (Nakano and White, 2007). In fact, the empirical measurement analysis in Chapter 3 will show that the simplistic hierarchy hypothesis for production industry sectors does not always hold.

2006).

They did not explain at a more fundamental level why firms in production markets tend to take more fixed positions and roles than firms in other types of markets. Also, there might also be gradual degrees of the tendency for positions and roles to become fixed, which would imply varied degrees of hierarchy in different industry architectures, with some intermediate situations between pure hierarchy and pure freedom. In addition, though their analysis considered such factors as quality and price as the rules that organize the hierarchical production markets, they overlooked possible technological influences imposed by the products (e.g. components and parts) that are innovated, developed, produced, and transacted (and flowing) in the these markets. This may lead to an incomplete understanding of hierarchy in industry architecture, simply because the industry sector is a social-technical system subject to both the invisible hand of the market and the visible hand of technology. This dissertation addresses these unexplored issues related to the hypothesis of hierarchy in industry architecture.

Classic supply chains (i.e. the chains of processes, inventories, or plants connected by shipments) display strict hierarchy. However, a focus on firms, rather than tasks or inventories, shows that clusters of firms may have linkages going in many different directions. In an industry sector that has a multi-layer structure with multi-step value-adding chains, a firm may perform multiple industry roles in different production stages. This makes the hierarchy of industry architecture potentially ambiguous (Jacobides, 2005; Jacobides, Knudsen, and Augier, 2006; Dalziel, 2007), and difficult to determine objectively. Essentially, hierarchy is not a zero-or-one phenomenon in industrial sectors, but varies gradually. Thus, robust methods are needed to objectively quantify, measure, and compare the hierarchical patterns of industry architectures, in order to answer such important questions as how hierarchical an industrial sector is (over time), or how hierarchical one sector is compared to others.

1.4.3 Three Questions

In fact, three fundamental and sequential questions underlie the hierarchy puzzle and determine the direction of further exploration and the methods needed:

Question 1): *Can we measure and compare the degrees of hierarchy of different sectors*?

Question 2): *How does sector-wide hierarchy emerge from the transactional interactions of single firms*?

Question 3): *What drives firms to behave differently or similarly in different sectors*?

1.5 Research Design

To answer these three questions, this dissertation research is divided into three major stages.

1.5.1 Three Research Stages

Stage 1: Defining and Measuring Industrial Hierarchy

In the first stage of research, I develop a network-based metric and related algorithm to quantitatively measure how hierarchical a real-world industry sector is and how its degree of hierarchy varies over time, and to compare the degrees of hierarchy of different industry sectors. I apply these metrics to networks of firms compiled from empirical transaction data on two industry sectors in Japan.

Stage 2: Linking Industry Architecture to Firm Transactions

In the second stage of research, I create a network simulation model to explore how industry architecture may emerge from the interactions of individual firms, especially how "the tendency of firms to fix their positions and roles" in aggregate may determine the variable degree of hierarchy of industry architecture. With such a model, we are able to link the sector-level hierarchy to firm-level transaction choices, especially transaction specificity (to be defined in Chapter 4), and thus learn about new aspects of industrial transactions at the firm level from the sector-level findings obtained in stage 1.

Stage 3: Understanding Firm Transaction Strategies

In the third stage of research, I try to further understand what leads to the possible differences or similarities in the transaction choices of firms in different sectors, revealed in stage 2. In particular, I explore why firms may have different tendencies to fix their positions and roles, by analyzing the influences of product technologies, which have been largely ignored by the economists and sociologists studying hierarchy and markets. I also seek insights by interviewing company managers about their transaction-related strategies and the underlying decision rationales.

Throughout this dissertation, four fundamental perspectives underlie the research design and distinguish this research from traditional industry studies. First, the unit of analysis is a sector, instead of the narrower industry. Second, I examine macro industry architectures rather than the relationships between two industry layers. Third, I view, measure, and model an industry sector as a network of manufacturers and suppliers, and conduct quantitative network analysis. Fourth, I define the *degree of hierarchy* of a sector, and this allows for non-hierarchical industry architectures. This design of research is aimed to explore the set of previously ignored knowledge on industrial transactions, which is valuable to single firms in designing strategies and managing operations but is not available from firm- and industry-level analysis.

To this end, this dissertation surveys and integrates concepts and theories from various fields, including sector (Malerba, 2002), industry architecture (Jacobides et al, 2006), hierarchy (Simon, 1962), modularity (Baldwin and Clark, 2000), transaction costs and the boundaries of firms (Coase, 1937; Williamson, 1985), innovation dynamics (Koh and Magee, 2008), systems engineering (Whitney, 1996), and network analysis (Newman, 2003), as well as those in economic sociology, specifically production hierarchy (White, 2002), market niche (Burt and Talmud, 1993), and industry roles and positions (White et al, 1976; 2002; Wasserman and Faust, 2004).

1.5.2 Expected Contributions

This dissertation makes the following contributions:

1) The first metric for the degree of hierarchy in networks, and the first quantitative empirical evidence of the variable degrees of hierarchy in industrial sectors, challenging the pure hierarchy hypothesis of the architectures of production industry sectors.
2) The first model with random tunable networks that may represent industrial networks. The model can be manipulated to explain how hierarchy at the sector level may emerge from the interactions of individual firms.
3) The concept and quantification of "transaction specificity," which quantifies the proximity of the network positions of a firm's customers. It indicates the firm's tendency to fix their roles, or where the transactions are oriented.
4) A socio-technical theory of how the industrial transaction choices of single firms are constrained by technologies and shape industry architectures.

Of interest to academics, the application of network analysis permits the level of analysis to be extended from an industry to a sector comprising multiple industries. This gives us a bird's-eye view to observe firm-level transaction behaviors and create new knowledge about firm-level transaction behaviors and strategies. In addition, this research includes the analysis of the physical properties of product technologies in order to understand inter-firm transaction patterns, and attempts to shed light on the potential linkages between physics and economics, which pure economic and sociology theories cannot explain.

For industry practitioners, this research suggests that industry architectures may follow partially predictable patterns, and that firms' choices for industrial transactions are under some predictable constraints imposed by the nature of the product technologies and the architectures of products. A better understanding of the linkages between industry architecture, firm transaction strategy, and product technology, in turn can guide companies to tailor transaction strategies to implicit technological constraints and to adequately explore strategic options made feasible by technologies.

1.5.3 Overall Framework of Research Design

This dissertation explores how firms are organized at the sector level, in order to understand how individual firms' strategic transaction choices may shape industry architecture, and how they are constrained by technology. The overall research design, including the methods and contributions at each stage, are summarized in Figure 1.3.

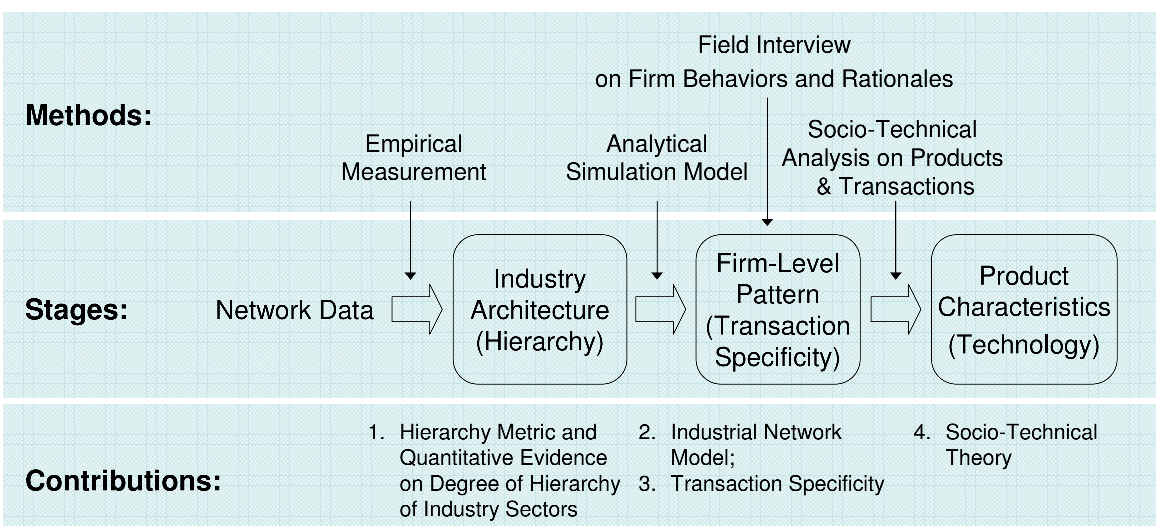

Figure 1.3 Overall research design

1.6 Guideline to the Dissertation

The remainder of the dissertation is organized as follows:

Chapter 2 reviews the theories of hierarchy, the typology of hierarchy in particular, and then identifies and defines the type of hierarchy that is most relevant and crucial for industry architecture analysis.

Chapter 3 introduces a network-based metric and algorithm to quantify and measure hierarchies and applies them to empirical transaction data from two large industry sectors in Japan: the automotive and electronics industry sectors. Significant differences are found between the degrees of hierarchy of the two sectors.

Chapter 4 introduces a network simulation model that relates the degree of hierarchy at the sector level to two more explainable variables at the firm level. The model is used to simulate sector-like stochastic networks with varied degrees of hierarchy.

Chapter 5 analyzes the findings from the field work in Japan. Interviews were conducted in Japan with industrial firms, with the aim of understanding the strategies and decision rationales of actual firms that may lead to the empirical and analytical results on industrial transactions that were found in Chapters 3 and 4.

Chapter 6 conjectures about how the nature of technologies may influence innovation dynamics and constrain firms' transaction behaviors, which in aggregate determine industry architectures. The analysis is socio-technical and is based primarily on the comparison of the two sectors' product architectures, innovation and production processes, transaction patterns, and industry architectures.

Chapter 7 concludes with potential future research directions that this dissertation suggests.

Chapter 2

Hierarchy in Industry Architecture

"It is a commonplace observation that nature loves hierarchies."

-- Herbert Simon

In this Chapter, I first review the literature on hierarchy theory, propose a generalized definition of hierarchy, and identify different types of hierarchy applicable to complex networks. I then focus on a particular type - a "flow hierarchy", which characterizes transactional relationships between industrial firms. A straight-forward approach is presented to extract and represent the flow hierarchy underlying real-world industrial networks, and demonstrate its limitations that will lead to the further work in Chapter 3 – the measurement of flow hierarchy.

2.1 Hierarchy Theory

Complex systems of various kinds (social, biological, physical, technological, etc) frequently take the form of hierarchy (Simon, 1962; Holland, 1998). On one hand, hierarchy is one of the central structural schemes that an architect may use to manage complexities. Products, organizations and other artifacts are often designed and managed hierarchically. On the other hand, hierarchies emerge and occur widely in self-organizing and evolutionary systems, such as food webs (ecological), neural networks (biological), open-source software (technological), and industrial supply chains (economic), etc., which have no architect. In such cases, it is viewed as a natural emergent phenomenon and the consequence of evolutionary processes (Simon, 1962; Agre, 2003; Holland, 1998).

An industrial sector is a complex system as it comprises many firms and interactions among them. Sectors often exhibit a blurry latent hierarchy (Coase, 1937; White, 2002; Malerba, 2002; Dalziel, 2007), as the central organizing scheme of the companies which complement, compete, collaborate and co-evolve in their sector. As the hierarchic systems often have some common properties that are independent of their specific contents, the general theories on hierarchy are potentially important for a deep understanding on industry architecture -- the central interest of this thesis.

The general theories on hierarchy attempt to answer fundamental questions like: What is a hierarchy? How many types of hierarchy are there? What are the common properties of hierarchic systems? How can we observe/measure, design and manage the hierarchies in actual systems? In the following I briefly review the literature which attempt to answer these questions.

The simplest definition of a hierarchy is: an ordered set (Ahl and Allen, 1996; Lane, 2006)[6]. In richer terms, a hierarchy is a collection of parts with ordered asymmetric relationships inside a whole, i.e. upper levels are above lower levels, and the relationship upwards is asymmetric with the relationships downwards, according to Ahl and Allen (1996). In general, hierarchy is a static architectural rather than temporal concept (Simon, 1962). And, the ordering of levels, i.e. the rule of asymmetry, determines a hierarchy. As a matter of fact, hierarchy is just one type of the generic architectural elements, while other possible architectures include symmetry, cycles, and periodicity (Heylighen, 1999).

Herbert Simon (1962; 1969) was the first to build a systematic theory of hierarchy in order to understand, design and manage complex systems. According to Simon, a hierarchic system, or hierarchy, is a system composed of interrelated subsystems, each of the latter being, in turn, hierarchic in structure until some lowest level of elementary subsystem is reached. This reductionist definition of hierarchy helps to describe and understand complexity, and design and manage complex systems. Centered on recursive decomposition, this view of hierarchy has been applied to analyses of product architectures, engineering decisions, innovation dynamics, and organizational and industrial changes (Marples, 1961; Christensen and Rosenbloom, 1995; Murmann and Frenken, 2006). The recent progress on extracting the hierarchies of complex networks also focus on this view of hierarchy (Clauset, Moore, Newman, 2008; Ravasz and Barabasi, 2003; Sales-Pardo, et al, 2007).

[6] I also collected definitions of hierarchy from other sources. Hierarchy is a graded or ranked series in Merriam & Webster dictionary. In ESD Terms and Definitions (2002), hierarchies create a ranking of elements in a system. In addition, in American Heritage Dictionary, hierarchy is a series in which each element is graded or ranked" or "a body of clergy organized into successive ranks or grades with each level subordinate to the one

However, for most of the complex systems in the natural world, the interactions among their subsystems are weak, but not negligible. “It is somewhat arbitrary as to where we leave off the partitioning and what subsystems we take as elementary” (Simon, 1962). Lane (2006) argued that it is harder to detect and categorize social level hierarchies than physical or biological ones, because they are not “inclusion hierarchies”.

In Simon’s seminal paper “*The Architecture of Complexity*”, the hierarchies formally defined and analyzed by Simon were always inclusion hierarchies following the rule of subordinating, although Simon was aware that he relation of subordination does not exist in some other types of hierarchic systems. In such cases, systems are no longer analyzable from a (nearly) decomposability perspective. Many other scholars (Anderson, 1977; Ahl and Allen, 1996; Holland, 1998; Lane, 2006) pointed to broader types of relations existing between the elements that may determine a hierarchy.

Allen (1998; Ahl and Allen, 1996) addressed several types of hierarchical relationships according to their different logic constructs on why a upper level is above a lower one: 1) being the context of, 2) offering constraint to, 3) behaving more slowly at a lower frequency than, 4) being populated by entities with greater integrity and higher bond strength than, 5) containing and being made of. They also offered the alternative and complementary concepts of nested hierarchy (similar to Simon’s) and non-nested hierarchy, for which examples include food webs and supply chains.

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above”.

Lane (2006) distinguishes four different kinds of "hierarchy" which partially overlap and partially contradict with each other: 1) order hierarchy, 2) inclusion hierarchy, 3) control hierarchy, and 4) level hierarchy. Order hierarchy is induced by the value of a variable, such as size, weight, social status, etc. It does not necessarily refer to relationships and interactions among the entities comprising the hierarchy. Inclusion hierarchy refers to a recursive organization of entities and is the one that Simon focused on. Control hierarchy often refers to social organizations, and is determined by who gave orders to whom, and the flowing of orders rank-downwards and information and requests rank-upwards. In level hierarchy, entities are posited at extending "levels" according to their spatiotemporal scales. Level hierarchy might be regarded as a specific type of order hierarchy induced by the variable "spatiotemporal scale".

Moses (2002; 2004) categorized the elementary system architectures that exist in biological, engineering, religious, social, economic systems, as well as natural and artificial worlds. They are family or team structure, tree structure, layered structure, and network structure (see examples in Figure 2.1). Among them, tree and layer are both regarded as hierarchical. Team and network structures are non-hierarchical in principle. Moses elaborated the disadvantages and advantages of different generic architectures in the context of systems architecting.

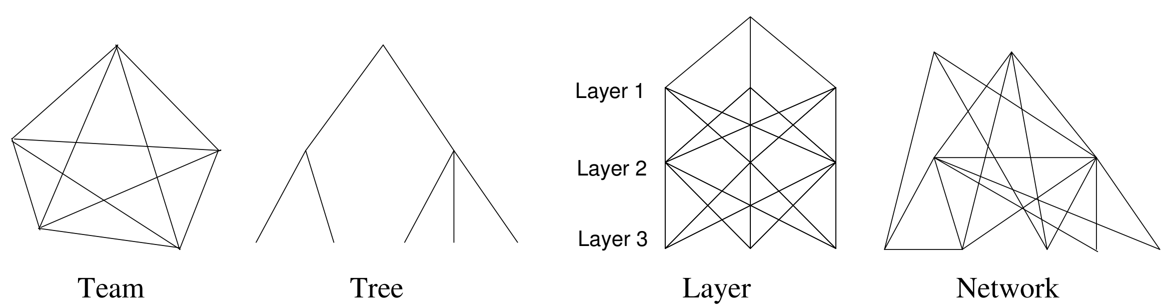


Figure 2.1 Examples for elementary architectures defined by Moses (2002; 2004)

In organizational economics, hierarchy is often used to mean the organizations with authorities (e.g., government, firms, and universities), as opposed to the autonomous markets (Williamson, 1975). Hierarchy and market are regarded as two conflicting and complementary organizing choices in the economy. Such an understanding and use of the word "hierarchy" implicitly refer to the "formal organizational hierarchy" of Simon (1962).

The diversity of views and foundational work aimed at creating a generalized hierarchy theory shows the difficulty to detect and use hierarchy in managing complexities. The difficulties are two-fold. First, hierarchy appears in various forms. Hence the shared vision on hierarchy by scholars from diverse fields also carries on varied meanings specific to their own contexts. Second, real systems may not be "pure" hierarchies of any of the theoretical types reviewed above, but a mix of order (or hierarchy) and randomness, despite the ordering intentions of human architects or the ordering tendency of evolution.

In the setting of an industry sector, such challenges remain – "hierarchy", though its type is has not been made clear in prior studies, is widely accepted but only fuzzily observed in the network of companies that co-exist in an industrial sector. A natural next step to advance our understanding on hierarchy in industry architecture is necessarily to identify the type of hierarchy relevant to industry studies, and develop measures of the deviation between the theoretical type of hierarchy depicting industry sectors and an actual industrial sector.

2.2 Typology of Hierarchy: Defining Flow Hierarchy

Following a number of varied definitions of hierarchy in the literature, here I propose a generalized version. I define hierarchy as ***a generic structure, in which levels are asymmetrically ranked according to a specific type of relation***. Since the industrial sector is to be investigated as a network of companies, the hierarchy typology applicable to networks is of our particular interest. By the logic construct for why an upper level is above a lower one, two types of hierarchies are useful for understanding the architecture of industrial sector network: **containment hierarchy** and **flow hierarchy**.

A containment hierarchy is similar to the concepts of “nested hierarchy” (Simon, 1962; Alexander, 1964; Christensen and Rosenbloom, 1995; Ahl and Allen, 1996; Tushman and Murmann, 1998; Murmann and Frenken, 2006) and “inclusion hierarchy” (Wilson, 1969; Lane, 2006; Murmann and Frenken, 2006). In a containment hierarchy, lower levels lie within or are aggregated into upper levels, and upper levels contain lower levels. The classic Russian dolls make up a containment hierarchy. Complex products like airplanes are often viewed as containment hierarchies, because they are made up of subsystems, which contain smaller components and parts (Tushman and Murmann, 1998). All containment hierarchies can be represented in terms of a pure tree or dendrogram (Wasserman and Faust, 1994; Clauset, Moore and Newman, 2008).

A flow hierarchy arises when there is directional movement through a series of stages. Flow hierarchy is observed in many evolving, self-organizing, and emergent networks such as food webs, neural networks, information processing networks and industrial production networks. For example, in the industrial setting, if firm B purchases a good from firm A, the good flows from A to B with the payment flowing in the reverse way. A classic supply chain is a pure flow hierarchy as components and parts flow from upstream processes or inventories to downstream processes or inventories. In a food web, energy flows. In a software routine network, it is information that flows as subroutines feed parent routines.

In many of these cases, the containment ordering criterion does not apply, and the order of levels (i.e. stages) is essentially determined by the direction of the flows of resources essential to the coherent goal of the system, such as goods, energy, materials, payments, or information. Such flows are crucial because they provide necessary resources, for the entities to produce, reproduce, sustain (or remain in useful or necessary existence) and prosper. Via being connected by flows, the entities co-evolve and may self-organize into a hierarchy.

The relation among entities may indicate which type of hierarchy is most appropriate for depicting a complex system or network. In fact, noticing the node-to-node relations crucial to system existence has led us to identify and term "flow hierarchy", independent of the specifics of the flows. In contrast, the mathematicians work on hierarchy from a different direction. They often first create a theoretical structure that has only mathematical meaning, and then adapt it as needed in order to find it in or apply it to various real-world contexts.

Flow hierarchy is one type of non-nested hierarchy (Ahl and Allen, 1996), but it is more specific in suggesting the significance of the flow directions in determining the asymmetrical ordering of the hierarchy. In contrast, the more general term "non-nested hierarchy" is not instructive for understanding industrial networks (our central interest). Thus, I prefer to use “flow hierarchy” when studying a specific system, such as supply network, software, or food web. The concept of flow hierarchy also overlaps with “level hierarchy” from Lane (2006) in most senses, while being more comprehensible as it does not address and require the identification of discrete “levels”[7]. Thus, level hierarchy may be regarded as one kind of flow hierarchy.

The flow hierarchy of a network can be described in terms of an acyclic directed network of nodes and links. It is only associated with directed networks, while a containment hierarchy can be found for both directed and undirected complex networks, in which nodes that are closely connected (Wasserman and Faust, 1994; Girvan and Newman, 2002; Sales-Pardo, et al, 2007; Clauset, Moore and Newman, 2008;), or have close equivalence measures (Wasserman and Faust, 1994; Hsieh and Magee, 2008), share lower common ancestors than more distantly connected or distinctly positioned nodes.

Thus a directed network may embed and exhibit both flow hierarchy and containment hierarchy. Figure 2.2 illustrates the distinction between these two alternative types of hierarchical representations for a single network. In Figure 2.2A, the solid balls are the actual entities connected by the flows in the tree network. The flow hierarchy of the network is self-explanatory. Figure 2.2B is a containment hierarchy representation of the network in Figure 2.2A, in which the squares stand for the subsystems (and the subsystems of subsystems) level by level, downward to the elementary entities (solid balls) of the network in Figure 2.2A. Most software systems can be well represented in both ways: a flow hierarchy -- a network of

[7] In the next chapter, we will show the value of this comprehensibility of the flow hierarchy concept for building a metric to measure the hierarchy of an industrial sector.

routines connected by information flows; as well as a containment hierarchy -- a tree of the system, decomposed into a number of subsystems, each of which may be further sub-decomposed, recursively, until reaching the individual routines.

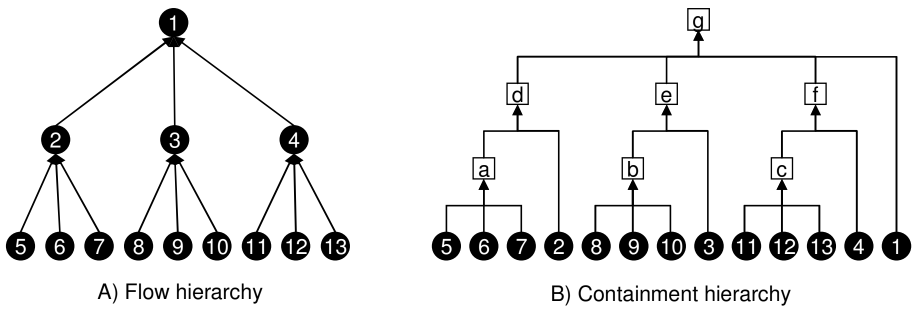


Figure 2.2 The alternative hierarchy representations of a single network.

In some cases, only one type of hierarchy is appropriate. In undirected networks, only containment hierarchy is applicable. Comparatively, in food webs, the relations among the species do not contain each other, while flow hierarchy can be used to describe food webs as energy flows among the species. In the industrial setting as in food webs, the concept of flow hierarchy is essential, because firms are involved and connected by the transaction flows to innovate and produce a coherent set of system products, while the firms do not contain each other.

However, the transactions flows between firms in an industry sector do not necessarily obey a strict asymmetric ordering. Hence industry architectures are not necessarily hierarchical. For example, FoxConn, the largest Taiwanese original design manufacturers (ODM) of personal computers, supplies finished computers directly to the personal computer makers, such as Dell and Apple, but it also produces and sells many connectors, cables, printed circuit board

(PCB), etc to other suppliers in the personal computer manufacturing sector. Thus, Foxconn's transactional relationships are directed both upstream and downstream. As a result, Foxconn's position in the sector hierarchy is ambiguous. And if most firms in the sector are like Foxconn, the sector will not be hierarchically organized. It is this puzzle of industry architecture that I am seeking to investigate both empirically and theoretically.

2.3 Representing Networks as Flow Hierarchies: A Layering Approach

Recently, progress have been made in extracting and representing the containment hierarchies of complex networks, by applying either the cohesive (Clauset, Moore, Newman, 2008) or equivalence (Sales-Pardo, et al, 2007) rules for decompositions at each hierarchical level. However, neither one-level decomposition nor recursive decomposition to find containment hierarchies have been applied to the analysis of inter-organizational or the firm-to-firm networks in an industrial sector. This may be largely because the appropriate representation for an industrial network is a flow hierarchy.

The abstract view of the hierarchically-tiered supply network architecture has been widely accepted in the manufacturing industries. In this view, the industry players on a higher tier (level) purchase parts and components from the industry players on a lower tier, obeying the flow hierarchy definition. Firms are defined into different tiers, such as assemblers, system suppliers, component suppliers, raw material suppliers, according to their roles reflected in their supply network positions (Dalziel, 2007). However, this layered positioning of firms in an industrial network, or nodes in a general directed network, is somewhat arbitrary as levels are often ambiguous. The representation of complex industrial networks as flow hierarchies need to be further exploited.

In many cases, there is no objective and definitive criterion according to which a network node must be on a specific level in these industrial networks, though experts with domain knowledge can give a level rank to a node based on their domain knowledge and subjective judgment. Such rank-assigning work based on domain knowledge is a usual practice in food web research (Dunne et al, 2008) and industrial system research (Dalziel, 2007), but have a partially arbitrary character.

In order to avoid arbitrary ranking of nodes in a directed network, I explore several practical ways of assigning each node to its respective level in a directed network, using the information of the network positions of the node. The ranking (i.e. level-assigning) algorithms first identify the sinks[8], which have no outgoing links but only incoming links, and then use the path lengths from the other nodes to sinks as the basis of assigning a level rank. Here, path length means the number of intermediate links on a path from a node to a sink of interest. A path is a walk in which all nodes and all lines are distinct; a walk is a sequence of nodes and lines, starting and ending with nodes, in which each node is incident with the lines following and preceding it in the sequence (Wasserman and Stanley, 2004).

In this way the sinks are used as the benchmarking boundary. Alternatively, the sources, which have no incoming links but only outgoing links, can also be used as the benchmarking

[8] In the industrial sector setting, sinks are the final assemblers often called OEMs, which produce the finished

boundary. In the following, I will only show the use of sinks as the benchmarking boundary as the analysis of sources is directly analogous. Because there is usually more than one path from a general node to a sink, and there are usually more than one sink on the top bound of the industry, five different algorithms are discussed. These algorithms are abstracted to different aspects of the relative network positions of nodes.

- **Min [Shortest]**: A node's level rank *LR* is given as the shortest one among all its shortest paths to all the sinks.

$$LR_i = \min(\min_j(D_{ij})) \quad i \in [nodes],\ j \in [sinks] \tag{2-1}$$

LR_i : the level rank of node *i*;

D_{ij} : the set of lengths of the paths from node *i* to sink *j*.

- **Max [Shortest]**: A node's level rank is given as the longest one among all its shortest paths to all the sinks.

$$LR_i = \max(\min_j(D_{ij})) \quad i \in [nodes],\ j \in [sinks] \tag{2-2}$$

- **Min [Longest]**: A node's level rank is given as the shortest one among all its longest paths to all the sinks.

$$LR_i = \min(\max_j(D_{ij})) \quad i \in [nodes],\ j \in [sinks] \tag{2-3}$$

- **Max [Longest]**: A node's level rank is given as the longest one among all its longest paths to all the sinks.

$$LR_i = \max(\max_j(D_{ij})) \quad i \in [nodes],\ j \in [sinks] \tag{2-4}$$

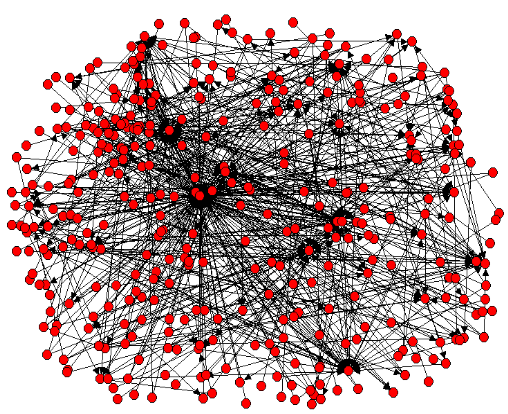
- **Continuous Level Rank (Average)**

goods for end users.

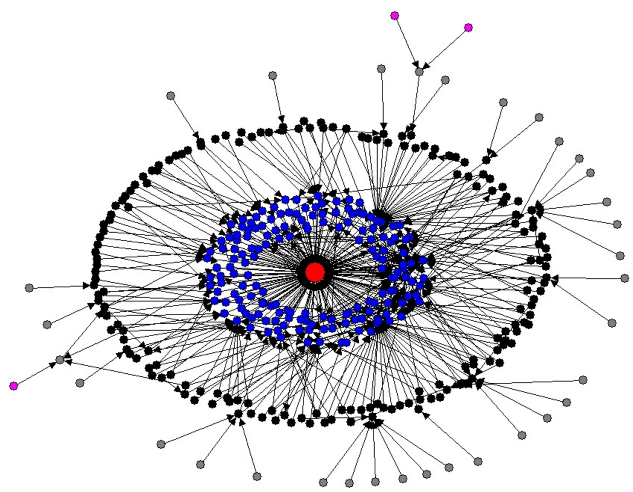
$$LR_i = \underset{j}{average}\,(D_{ij}) \quad i \in [nodes],\ j \in [sinks] \tag{2-5}$$

Note: when there is only a single sink in the network, Max [Shortest] and Min [Shortest] become the same, and Max [Longest] and Min [Longest] become the same.

The first four algorithms above tend to group the nodes into discrete levels, while the fifth algorithm is different because it assigns continuous level ranks. Figure 2.3 shows the example of the network of Toyota Motor Company's suppliers before and after being grouped into their respective levels, using the Max [Shortest] algorithm. In Figure 2.3, the nodes (i.e. firms) are arranged in space (using the software package UCINET) to illustrate the underlying level hierarchy, i.e. a special kind of flow hierarchy. Based upon the arbitrary ranking/grouping result, this visualization exhibits strong hierarchy, including three levels of suppliers below the sink level in Toyota's supplier network.



A) Before grouping



B) After grouping

Figure 2.3 The network of Toyota's suppliers (A) before grouping and (B) after grouping based upon the *Max [Shortest]* algorithm.

Note: The network contains the Japanese suppliers either directly or indirectly connected to Toyota by the flows of transacted components and parts. For instance, if company A sells a product to company B, there is an arrowed link from A to B in the network. The network is extracted from the data book by Dodwell Marketing Consultants (1993), and includes 372 nodes (i.e., manufacturing firms) and 591 links (i.e. supplier-customer transactional relationships). The red node in the middle of graph B) is Toyota Motor Company.

This way of extracting network levels to represent complex networks as flow hierarchy is somewhat arbitrary in choosing the ranking algorithms, although it may provide potentially simplified views of the architecture of complexity by abstraction. Given a more complex network in which flow hierarchy is less tangible, a visualization based upon this approach may abstract the reality too much.

2.4 Chapter Summary

In this Chapter, hierarchy theory and typology are reviewed. I then identify and define a specific type of hierarchy -- “flow hierarchy”, which is most relevant to industry architectures. Then, a real-world industrial network example, Toyota Supplier Network in Japan (1993), was abstracted and visualized as a flow hierarchy, using a straight-forward ranking-based approach. Facing the limitations and arbitrary nature of extracting hierarchical levels, in Chapter 3 I will propose a way to objectively evaluate flow hierarchies impurely existing in actual networks.

Chapter 3

Measuring Hierarchy in Industry Architecture

"Everything should be made as simple as possible, but not one bit simpler."

-- Albert Einstein

The previous chapter has discussed the value and limitations of using flow hierarchy to characterize the transaction relationships between industrial firms in an industrial sector. In this chapter, I present a way to measure how much a given industrial sector deviates from the standard of a pure flow hierarchy, based upon a new metric for measuring the hierarchy in directed networks.

3.1 The Complexity of Architectures[9]

How complex or simple we perceive a system to be depends on the way it can be described (Simon, 1962). In other words, the complexity of a system may be interpreted as the degree to which the total reality can be best described by our existing knowledge of a certain kind of

[9] Please note that I am going to discuss "The Complexity of Architectures", rather than "The Architecture of Complexities" from Simon (1962). By this term, what I emphasize is comprehensiveness rather than abstraction.

order or regularity, with minimum additional complications created in applying the existing knowledge. If there is no existing knowledge on the regularity embedded in a system, its complexity is at its maximum.

In the analysis of industrial architectures, the order or regularity is in the forms of architecture patterns, such as modularity, hierarchy, etc. Architectures, expected as simplified truth for complex systems, are useful abstractions that reduce cognitive difficulties, or the lens that researchers can use to probe complex systems. Using existing architectural knowledge, we can understand at least part of a system. Meanwhile, architectures with known functions may also be used to guide the design and management of systems. However, architecture may trade reality for simplicity. That is, architectures are useful at the expense of certain degree of information loss or additional complications from applying them.

In simple and idealized systems, such as "tree-like" organizational charts, hierarchy is clean and easy to observe. So, using appropriate hierarchical patterns to interpret such organizations has little reality loss or additional complication generated. Such organizations may not be regarded as complex in spite of their large sizes. However, in the cases with large complexities, the best architectural representations, which maximize the understanding of the regularity of a system, may still leave a large part of the system unknown or unrepresented. In addition, the use of an architectural pattern to interpret a system may even add new complications or noise to original system. These issues are the sources of complexities that the analysis of architectures may involve. Therefore, from an architectural perspective, the complexity of a system can be represented as,

$$\textit{Complexity} = \textit{Reality} - \textit{Understood Architectural Knowledge} + \textit{Noise from the Use of the Architectural Knowledge} \quad (3\text{-}1)$$

Thus, what we need is to minimize this function of complexity in two aspects: 1) finding the most appropriate architecture pattern (i.e. limiting reality loss); 2) limiting the additional "noise" generated by the use of the chosen architectural pattern.

Therefore, when focusing on an architectural paradigm, such as flow hierarchy, we are aware that it may just partially represent the truth although we consciously or unconsciously expect it to do it fully. We also need to be clear about which part of the reality is unrepresented and what additional noise is added to the reality. They need to be carefully taken care of, or comprehended, especially when they are not negligible.

Based upon this view, the first thing to reduce the complexity of a system is to identify the most relevant architectural pattern and use it as a lens to probe the system, so that reality loss can be limited. In the previous chapters, I have identified flow hierarchy as the most relevant hierarchical pattern in industrial network analyses, because industrial firms often self-arrange into a flow hierarchy, whose order of levels is essentially determined by the direction of the transacted flows of materials, components and parts. However, detecting and comparing flow hierarchies are still difficult in many real-world self-organizing networks, including industrial networks, largely because either hierarchy or other alternative architectural patterns usually appear in impure forms. This leads to the question on the second factor in equation (3-1) that also affects the complexity of system architecture analysis – the noise created in applying a specific architectural pattern.

Therefore, an appropriate network analysis approach needs to be capable of comprehending the unrepresented part of the reality of the network while limiting extra complications brought by the analysis itself. Watts and his colleagues (Watts and Strogatz, 1998; Dodds, Watts and Sable, 2003; Watts, 2003) have taken a similar perspective in the ways they build network models to represent actual systems -- any real-world systems can be understood and modeled as a mix of two extremes: order and randomness. The regularity or architecture of a system is what we look for, while the randomness may adequately represent what is unknown or irregular. Simon (1962) also created the concept of “near decomposability” to comprehend the unrepresented but necessary part of the reality of a complex system, when taking advantage of the abstractness of architectures.

The approaches developed in this thesis will address these challenges from the complexity of architectures, by appropriate abstractions and enough comprehensibly.

3.2 Literature Review: Empirical Network Analysis

The analysis of flow hierarchies in industrial sector networks is essentially grounded by network analysis theories and methods, as it is an architectural element of directed networks. There are two major strands of literature in general network analysis: 1) empirical analysis, and 2) analytical models, relevant to the methodologies developed in this thesis for analyzing industrial networks. In this chapter I mainly review the literature on empirical network analysis as I mainly focus on the measurement of hierarchy in industry architecture. The literature on the analytical network models will be reviewed in Chapter 4, which focuses on an industrial network model.

Empirical network analyses probe the simplified properties or patterns underlying the complex large-scale network data in order to make them recognizable. Different kinds of network patterns or properties require different analysis methods. Usually, empirical network analyses use two types of methods: Graph theory metrics, and decomposition, i.e. community finding.

3.2.1 Graph Theory Metrics

Network analysis based upon graph theory has been conducted to understand a variety of network systems, including the Internet, transportation systems, electricity grids, citation networks, social networks, biological networks, ecological networks, etc (Newman, 2003). In particular, the graph theory metrics, such as centrality, prestige, clustering coefficient, etc (Wasserman and Faust, 1994), provide ways to capture the architectural properties with considering overall information throughout a network. Such metrics of nodes taken together may reveal some collective properties of networks, such as the small-world effect (Watts and Strogatz, 1998).

Degree[10] distribution of large networks has been studied as a pattern of large-scale networks. Many real-world networks, including the internet, metabolic reaction network, telephone call

[10] The degree of a vertex in a network is the number of edges connected to that vertex. In directed networks, in-degree is the number of incoming edges, and out-degree is the number of outgoing edges.

network, etc (Strogatz, 2001; Newman, 2003), exhibit a highly skewed degree distribution, and the distribution decays as a power law,

$$p(k) \sim k^{-r} \tag{3-2}$$

where k is the degree of a vertex, $p(k)$ is the fraction of nodes in the network that have degree k. Particularly, the exponent r is often in the range of 2.1~2.4 in the studied cases.
Price (1965) was probably the first one to discover the power-law distribution of a network – the network of citations between scientific papers. He found that both in- and out-degrees (number of times a paper has been cited and number of other papers a paper cites) follow power-law distributions. The power-law distribution of networks implies a small number of nodes are highly more connected than most of the others. This class of networks with power-law degree distributions is often referred to as *scale-free networks* (Barabasi and Albert, 1999).

Small-world effect is another important collective property discovered in a variety of large-scale networks (Watts and Strogatz, 1998; Newman, 2003), ranging from collaboration networks to power grids or neural networks. Small-world effect indicates that most pairs of vertices in a network can be connected by a relatively short path and yet the clustering effect is high. A small-world effect was first revealed in a social experiment carried out by Stanley Milgram (1967) in the 1960s, in which letters were passed from person to person and were able to reach a designated individual via only a small number of intermediate persons. Watts and Strogatz (1998) suggested that the small-world effect is the result of the coupling of two network properties: short path and high clustering. Nodes are highly clustered locally meanwhile the clusters are sparsely connected, so the pairs of nodes can be connected in relatively few steps[11]. And small-world networks may have advantages in signal-propagation speed, computational power, and synchronizability (Watts and Strogatz, 1998).

Graph theory metrics have not been widely applied to industrial network analysis. In the limited literature in this regard, Nakano and White (2006) quantitatively tested the small-world hypothesis (checking the clustering coefficient and average path length) and scale-free hypothesis in the large-scale supplier-customer network in the Tokyo industrial district. Both hypotheses were rejected. Alternatively, their analysis found that the directed acyclic graph (DAG) best explained the structural properties of the industrial network. DAG is a pure flow hierarchy following our definition. They also extended to suggest that DAG should be a general property for complex production networks. However, our measurement analysis (upcoming in Section 3.6) will show that the DAG hypothesis does not hold for one of the industrial sectors in our datasets.

3.2.2 Decomposition

Another strand of empirical network analysis aims to detect the communities or modules in large-scale real-world networks. Abstracting a large-scale complex network into a small number of communities or components may largely reduce the cognitive difficulty. A wide range of network decomposition techniques has been created by researchers from various fields, including social network analysis, computer science, physics, etc, in order to discover the natural divisions of networks into subgroups. The rich network decomposition methods

[11] Most often, nodes are separated by only "six degrees" regardless of the network size (Watts, 2003).

can be classified into two broad classes: 1) one seeks cohesive subgroups (Wasserman and Faust, 1994; Girvan and Newman, 2002); 2) the other seeks equivalence subgroups (Wasserman and Faust, 1994; Hsieh and Magee, 2008).

Usually, at the first step to decompose a network, nodal equivalence similarity or closeness measures are calculated. With the similarity measures, either agglomerative hierarchical clustering (Wasserman and Faust, 1994) or k-means algorithm (Lloyd, 1982) can be used to construct a pure tree-like dendrogram (Clauset, Moore and Newman, 2008; Wasserman and Faust, 1994), in which nodes are divided into groups that are further divided into subgroups of groups and so on over multiple levels. Nodes that are closely connected, or have close equivalence measures, share lower common ancestors than more distantly connected or distinctly positioned nodes.

At the next step, the optimal number of sub-groups and the corresponding members of each sub-group are determined by cutting the dendrogram at the level where the "*modularity*" or other metric is maximized. Newman and Girvan (2004) and Hsieh and Magee (2007) have developed algorithms that maximize the "*decomposability*" defined respective to cohesion and equivalence rules. In addition, the software architecture studies often do not create the dendrogram, but directly manipulate the Dependency Structure Matrix (DSM) in order to discover and manage the modules of software networks (MacCormack, Rusnak and Baldwin, 2006), and the underlying decomposition rule is often cohesion.

In general, these methods mainly focus on one-level decomposing. Recently, some progresses have been made in the criteria and methods to detect the most appropriate dendrogram (Sales-Pardo et al, 2007; Clauset, Moore and Newman, 2008) for a network, i.e. the hierarchical decompositions of the network -- containment hierarchy.

In contrast, flow hierarchy in networks has received relatively less attention in the network sciences community. Some research has been done to identify order hierarchy or level hierarchy (Lane, 2006) of networks which may be better depicted as flow hierarchies. Trusina, et al (2004) used each node's degree as a proxy for its importance in order to rank the nodes and indentify the embedded hierarchy. Though they did not specify the typology of the hierarchy which they studied, in fact it is "order hierarchy" according to the definition of Lane (2006). Dalziel (2007) in industrial economics and Dunne et al (2008) in food web research used their domain knowledge to determine which nodes are on which levels of the hierarchies, in industrial sectors and food chains respectively. The hierarchies they examined are level hierarchy. However, they use no information about network positions to indentify levels. Hsieh and Magee (2009) presented a method for decomposing a network into an optimal number of automorphically-equivalent sub-groups, and suggested that the relationships among the resulted subgroups may exhibit a flow hierarchy.

Nakano and White (2007) decomposed the Japanese supplier-buyer network in Tokyo industrial district into discrete levels. Because the supplier-customer relational linkages in their regional industrial network are strictly oriented (non-reciprocal), the chains of these oriented links run in the same direction, "top" to "bottom" for each chain, and do not form cycles. Their network is a directed acyclic graph (DAG), i.e. a pure flow hierarchy based on our definition in Chapter 2. However, how to assign a level rank to each node in a DAG is not uniquely defined because chains are of different lengths[12] and intersect in different places. Multiple ways of assigning level ranks may be sociologically meaningful, and Nakano and White (2007) used two different level assignment algorithms, minimal longest-chain levels (MLcL) assignment and maximally cohesive level (CoSL) assignment, which are similar to the Max [Shortest] and Min [Shortest] algorithms demonstrated in Chapter 2. An objective approach to quantitatively detect the "flow hierarchy" embedded in real-world complex networks, particularly industrial networks, is still lacking in the literature.

In addition, the empirical research on food webs and software also use network-based methods which are potentially applicable to industrial network analysis. These networks reflect the "prey-predator" type of relations similar to that between the suppliers and buyers in industrial networks, and flow hierarchy is potentially useful for interpreting them. In brief, the analysis on the architectures of food webs so far mainly utilizes the graph theory metrics, largely ignoring the essence of the flow directions (Dunne et al, 2008; Strogatz, 2001). The software architecture studies still focus on detecting modules and their functional implications, rather than either containment or flow hierarchies (MacCormack, Rusnak and Baldwin, 2006).

3.3 Imperfect Flow Hierarchy in Networks

As suggested in section 3.1, how complex or simple a system we perceive really depends on the way it can be described. This in turn depends on: 1) whether the most appropriate

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[12] Length – the numbers of unidirectional firm-to-firm relationships on a chain between two firms.

architecture is used to describe the system with limited loss of reality, 2) whether the architecture is analyzed in a way which minimizes the noise added to reality.

In the foregoing sections, I have identified and defined the type of hierarchy – flow hierarchy, most relevant to the industrial network analysis. Despite this, interpreting the actual industrial networks as flow hierarchies may be still a complex task, partly because flow hierarchies usually do not appear in a pure form in the complex networks. In the following, several simple examples are used to demonstrate the pure and impure existences of flow hierarchy in directed networks.

Many flow hierarchies can be graphed as "tree networks", such as a military chain of command, where each node is assigned not only a rank, but a single link to a higher up node. A tree is a generic hierarchical structure for a network. A classic tree hierarchy is shown in Figure 3.1A.

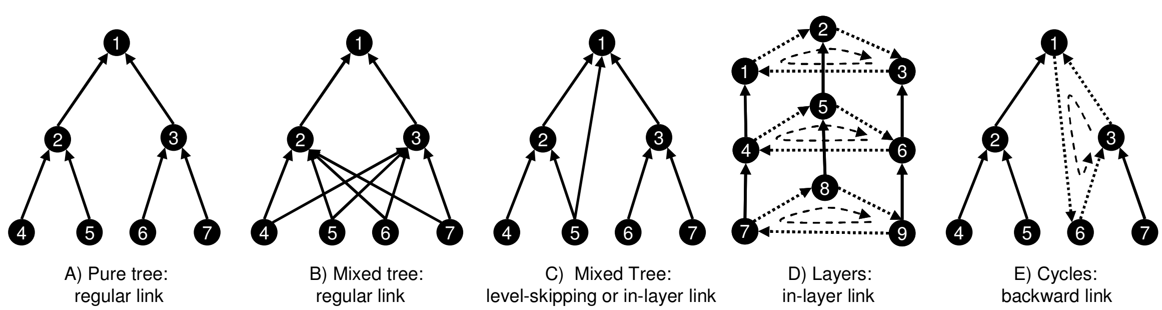

Figure 3.1 Generic structure and link types in example networks. Dashed links are involved in cycles.

The first variant from the pure tree hierarchy arises when a node has multiple inbound and outbound links, as demonstrated by Figure 3.1B. I call this a "mixed tree hierarchy". Both the pure tree and the mixed tree are strictly hierarchical because all the links connect from a lower level to an adjacent higher level. Hence there is strict asymmetric ordering of relationships. The links in Figure 3.1A and 3.1B are all "regular links".

In the third case shown in Figure 3.1C, a link is shown to skip its adjacent pre-identified level. I call this a "level-skipping" link. The network in Figure 3.1C can be viewed as a mixed tree, with level skipping. Level-skipping links make it difficult to assign an unambiguous level rank to a node. This in turn makes it difficult to organize a given flow hierarchy into layers or stages. Indeed, this is one of the key challenges in designing a hierarchy metric. Identification of level-skipping links and in-layer links relies on the pre-identification of layers. For example, in Figure 3.1C, if node 2 and 5 are defined to be in the same layer, the link from node 5 to 2 can be viewed as an "in-layer link", while the link from node 5 to 1 no longer skips a level and becomes a regular link. Partially because of level-skipping, as shown in section 2.3, the levels in a real-world industrial network often cannot be uniquely identified.

Networks often exhibit layered structures (Moses, 2004), i.e. level hierarchy (Lane, 2006), as shown in Figure 3.1D. In this example, if the nodes in the same directed cycle are presumed to be in a layer, there are "in-layer links" between firms, but flows proceed in one direction from layer to layer. A layered hierarchy emerges only if the links between layers are hierarchical.

Both level-skipping and in-layer links are still hierarchical (Moses, 2002; 2004). However, in the example in Figure 3.1E, a link connects from a pre-identified higher level backward to a lower one, i.e., a cycle emerges in the network. This violates the fundamental principle that, in a flow hierarchy things move in one general direction.

Ideally, given a criterion used to link levels above and below, the links from a predefined lower level to its adjacent higher level are regarded as hierarchical. In the simple examples in Figure 3.1, we observe regular links, in-layer links, level-skipping links and backward links. Among them, the first three types are hierarchical because the links connect from a lower layer to a higher or same layer, while a backward link is not. However, with all these irregularities aggregated in large complex networks, as well as the arbitrary nature of link type identification base on level assignment, flow hierarchies may become ambiguous and intractable.

Figure 3.2 visualizes two random networks with the same numbers of nodes (n=100) and links (m=400), but vastly different degrees of hierarchy. It is not surprising but important that such visualization while sometimes useful does not allow one to objectively see significant differences in hierarchy between different networks. In contrast, the hierarchy metric and the measuring technique to be introduced in next section will reveal the large difference in terms of flow hierarchy between these two networks: the network B is in fact three times more hierarchical than network A. This can be found by applying the hierarchy metric introduced in next section.

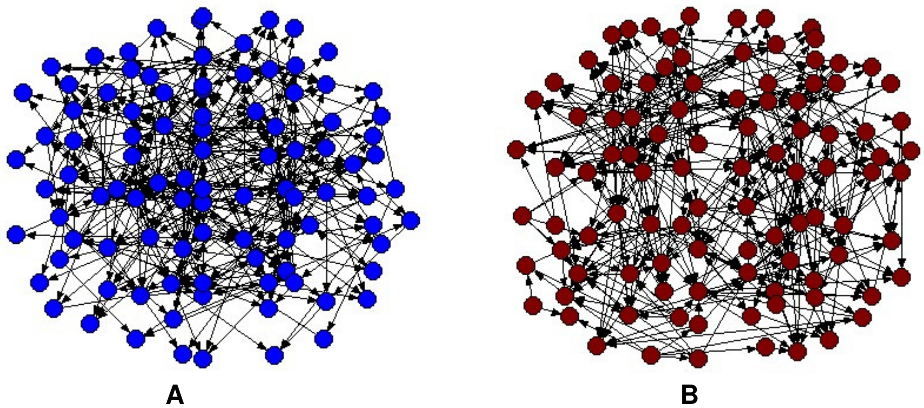

Figure 3.2. Random networks with the same size: the same number of nodes (n=100) and the same number of links (m=400).

3.4 Metric for Flow Hierarchy in Networks

Real world systems are often a mixture of various generic structures, including tree, layer, cycle, in particular. The co-existence of generic structures within the same network makes it difficult to detect the imperfect hierarchy architecture. For this reason, the ways of identifying hierarchy discussed in previous sections have shown limited values. Now I begin to quantitatively define the degree of hierarchy in an industrial network, and present a method to detect and measure it so as to avoid most of these difficulties.

3.4.1 Definition and Algorithm

An appropriate hierarchy metric must be unambiguous in differentiating the hierarchical components and non-hierarchical components in order to measure how hierarchical a network system is. If we choose to measure hierarchy by identifying hierarchical and non-hierarchical links, a predefined ordering of levels is required, as discussed in Chapter 2. However, in many cases, levels are ambiguous and must be decided through subjectively chosen rules.

In comparison, if we focus on identifying hierarchical and non-hierarchical generic structures, the metric can be unambiguous and consistent. In particular, tree and layer are regarded as hierarchical structures because of their asymmetric nature, while a cycle is not (Moses, 2004) because links in a cycle are symmetrical to each other so it violates our hierarchy definition. This way of decomposing hierarchical and non-hierarchical components, without the need for arbitrary level ranking, is actually the basis for the unambiguous hierarchy metric to be introduced.

Centered on the concept of flow hierarchy, I present a hierarchy metric (*h*) that detects and measures the extent to which all the local flows follow a holistic overall "underlying direction". As shown by the examples in Figure 3.1, cycles violate directionality which determines flow hierarchy in a network. Thus, the hierarchy metric is calculated as the percentage of links that retain their overall direction in the network, i.e., the percentage of links that are not included in any cycle,

$$h = \frac{\sum_{i=1}^{m} e_i}{m} \tag{3-3}$$

where m is the number of links in the network and e_i=0 if link i is in a cycle (1 otherwise). In weighted networks, the metric can be calculated as the ratio of the weights of the links which are not included in any cycles over the total weight of all links,

$$h_w = \frac{\sum_{i=1}^{m} w_i e_i}{\sum_{i=1}^{m} w_i} \qquad (3\text{-}4)$$

where w_i is the weight of link i. In the present thesis, I will focus on unweighted networks. Generally speaking, by focusing on differentiating the hierarchical and non-hierarchical generic structures, this metric is uniquely defined -- unambiguous and deterministic.

Hierarchy degrees for several typical example networks are calculated and shown in Figure 3.3. Networks A and B in Figure 3.3 are used to demonstrate the correlation between the overall system direction and local cycles in a directed network. In the acyclic network in Figure 3.3A, all local flows proceed in one general direction, no cycle exists. Thus it is purely hierarchical and h=1. Network B is almost the same as A, but has two extra links, which cause a cycle. Thus the overall asymmetry of the network is diminished to some degree but there is still some "imperfect" hierarchy present. The network is no longer purely hierarchical, and h=0.79. Network C is a directed tree, which is a pure hierarchical structure, so its hierarchy degree is 1. Network D is a pure cycle thus h=0. Network E presents a layered hierarchy, in which all the nodes are involved in cycles, but there are 2 clean layers connected by a hierarchical link in between. Its hierarchy degree is 1/7. The metric performs well in assessing layered hierarchy but numerous other potential metrics do not (see Appendix A). It is also advantageous in its clarity and ease of computation, in comparison to other potential metrics (An assessment of alternative metrics is provided in Appendix A).

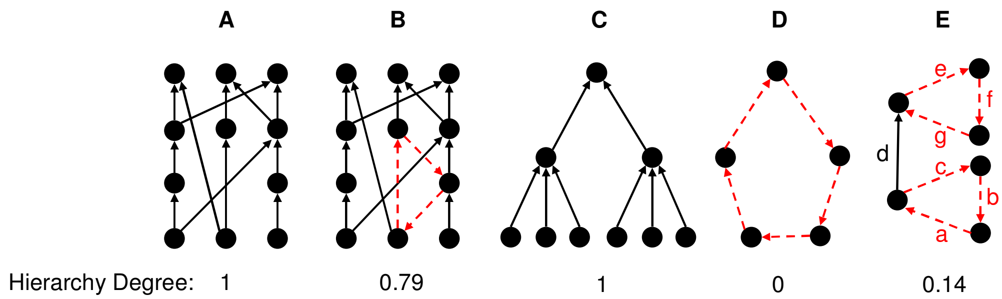

Figure 3.3 Example networks and corresponding hierarchy degrees. The dashed lines indicate cycles.

To compute the flow hierarchy metric for large-scale complex networks, I use the following algorithm: First, I construct the link adjacency network and matrix for the original node adjacency network. For example, Figure 3.4 shows the link adjacency network transformed from and equivalent to the original node adjacency network in Figure 3.3E. The 7 squares in Figure 3.4 correspond to the 7 links of the network of Figure 3.3E respectively.

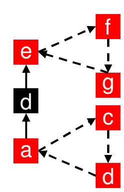

Figure 3.4 The link network equivalent to the network in Figure 3.3E

We name the cell (i,j) in the link adjacency matrix x_{ij}. $x_{ij} = 1$ if and only if the end of link i is directly connected to the start of link j by a node. Otherwise, $x_{ij} = 0$. Second, I raise the link adjacency matrix's power p to find the link distance matrix M_d. I name the cell (i,j) in the link distance matrix d_{ij}. d_{ij} is the distance from link i to j, defined as the minimum number of unique nodes which a uni-directed flow has to travel through from the end of link i to the start of link j. d_{ij} is found as the value of the power, at which cell (i,j) of the power matrix M^p has a non-zero value for the first time.

When p=1, the power matrix M^1 is the same as the link adjacency matrix, so that if x_{ij}=1, the distance from i to j is 1. If x_{ij} =0, and $x^{[2]}_{ij}$>0, then the distance is found as 2. And so forth. Consequently, the first power p for which the $x^{[p]}_{ij}$ element is non-zero gives the distance from i to j, i.e. the value of d_{ij} in the link distance matrix M_d. Mathematically, $d_{ij} = \min_p x^{[p]}_{ij} > 0$, for p from 1 to m, the total number of links (equal to the length of the longest possible cycle of links). I leave d_{ij} empty if the end of link i is neither directly or indirectly connected to the start of link j. Note that alternative algorithms, such as depth-first search, can also be applied to find the link distance matrix.

Figure 3.5 illustrates the process to derive the link distance matrix for the network shown in Figure 3.3E (equivalent to Figure 3.4). M^p and the M_d with the state of knowledge after p steps are paired. M^1 is the link adjacency matrix for the network in Figure 3.3E. The distance identified at each intermediate step is bold and its cell is shadowed. The M_d paired with M^6 is the final link distance matrix.

M^1

	a	b	c	d	e	f	g
a	0	0	**1**	**1**	0	0	0
b	**1**	0	0	0	0	0	0
c	0	**1**	0	0	0	0	0
d	0	0	0	0	**1**	0	0
e	0	0	0	0	0	**1**	0
f	0	0	0	0	0	0	**1**
g	0	0	0	0	**1**	0	0

M_d

	a	b	c	d	e	f	g
a			**1**	**1**			
b	**1**						
c		**1**					
d					**1**		
e						**1**	
f							**1**
g					**1**		

M^2

	a	b	c	d	e	f	g
a	0	**1**	0	0	**1**	0	0
b	0	0	**1**	**1**	0	0	0
c	**1**	0	0	0	0	0	0
d	0	0	0	0	0	**1**	0
e	0	0	0	0	0	0	**1**
f	0	0	0	0	**1**	0	0
g	0	0	0	0	0	**1**	0

M_d

	a	b	c	d	E	f	g
a		**2**	1	1	**2**		
b	1		**2**	**2**			
c	**2**	1					
d					1	**2**	
e						1	**2**
f					**2**		1
g					1	**2**	

M^3

	a	b	c	d	e	f	g
a	**1**	0	0	0	0	**1**	0
b	0	**1**	0	0	**1**	0	0
c	0	0	**1**	**1**	0	0	0
d	0	0	0	0	0	0	**1**
e	0	0	0	0	**1**	0	0
f	0	0	0	0	0	**1**	0
g	0	0	0	0	0	0	**1**

M_d

	a	b	c	d	e	f	g
a	**3**	2	1	1	2	**3**	
b	1	**3**	2	2	**3**		
c	2	1	**3**	**3**			
d					1	2	**3**
e					**3**	1	2
f					2	**3**	1
g					1	2	**3**

M^4

	a	b	c	d	e	f	g
a	0	0	1	1	0	0	**1**
b	1	0	0	0	0	**1**	0
c	0	1	0	0	**1**	0	0
d	0	0	0	0	1	0	0
e	0	0	0	0	0	1	0
f	0	0	0	0	0	0	1
g	0	0	0	0	1	0	0

M_d

	a	b	c	d	e	f	g
a	3	2	1	1	2	3	**4**
b	1	3	2	2	3	**4**	
c	2	1	3	3	**4**		
d					1	2	3
e					3	1	2
f					2	3	1
g					1	2	3

M^5

	a	b	c	d	e	f	g
a	0	1	0	0	2	0	0
b	0	0	1	1	0	0	**1**
c	1	0	0	0	0	**1**	0
d	0	0	0	0	0	1	0
e	0	0	0	0	0	0	1
f	0	0	0	0	1	0	0
g	0	0	0	0	0	1	0

M_d

	a	b	c	d	e	f	g
a	3	2	1	1	2	3	4
b	1	3	2	2	3	4	**5**
c	2	1	3	3	4	**5**	
d					1	2	3
e					3	1	2
f					2	3	1
g					1	2	3

M^6

	a	b	c	d	e	f	g
a	1	0	0	0	0	2	0
b	0	1	0	0	2	0	0
c	0	0	1	1	0	0	**1**
d	0	0	0	0	0	0	1
e	0	0	0	0	1	0	0
f	0	0	0	0	0	1	0
g	0	0	0	0	0	0	1

M_d

	a	b	c	d	e	f	g
a	3	2	1	1	2	3	4
b	1	3	2	2	3	4	5
c	2	1	3	3	4	5	**6**
d					1	2	3
e					3	1	2
f					2	3	1
g					1	2	3

Figure 3.5 Deriving link distance matrix by raising power of link adjacency matrix

Given the link distance matrix, we are able to judge if a link is on any directed cycle by examining the values on the main diagonal. In particular, the values on the diagonal of the final M_d after 5 steps give the length of the shortest link cycles in which each link is included. If d_{ii} is empty, then link *i* is not involved in any cycle (i.e. e_i=1, 0 otherwise). For the final link distance matrix of Figure 3.3E, only d_{dd} is empty, and this agrees with our direct observation on Figure 3.3E -- only link *d* is not included in any cycle. Thus, this network's flow hierarchy degree is 1/7 because 1/7 of the links are not involved in a cycle.

This metric of flow hierarchy has a wide applicability in other network systems, including intra-organizational networks, team networks, product component networks, etc. For more details on its wide applications, as well as its ability to detect the evolving patterns of self-organization networks, please see Appendix B. This thesis focuses on its uses in analyzing industrial networks.

3.4.2 Flow Hierarchy of Random Networks and *z*-score

Random networks can be used as valuable benchmarks for understanding the properties of empirical networks (Newman, 2003; Milo et al, 2004). Here I not only theoretically explore the flow hierarchical aspect of architectural properties of pure random networks, also apply them as the benchmark of the comparison in flow hierarchy degrees of different empirical networks.

By definition, a pure random directed network embeds no hierarchy. However, the hierarchy degree is not necessarily zero for the networks created by existing random network models. I have examined hierarchy degrees of networks generated by a simple model similar to the "Poisson random network" (Newman, 2003). Networks are constructed by assigning *m* directed links to randomly chosen pairs from *n* nodes. No multiple uni-directed links between a chosen pair and no self-links are allowed.

The directed Poisson random networks alone also exhibit important properties regarding hierarchy. Figure 3.6A shows that network size (*n)* has little influence on hierarchy degree (*h*), especially when *n* is sufficiently large. This agrees with our intuition that hierarchy is an architectural property independent of scale, and allows one to use random networks with a relatively small *n* to estimate *h* of those with large *n* but the same average degree *k* (=*m/n*)[13].

Figure 3.6B shows the increase of average degree (*k*) significantly decreases *h*[14]. When *k* is at its minimum 1/*n*, *h* will be exactly 1, because only one pair of nodes will be connected and one node is unambiguously above the other in this dyad flow hierarchy. When *k* is sufficiently high, *h* tends to zero because there are many cyclic pathways through which flow can travel back to its origin. A holistic direction does not exist among links in densely connected random networks. These results are of use to benchmark and compare *h* found from empirical networks.

[13] For an undirected network, average degree *k* =2*m/n*. For a directed network, average degree *k* =*m/n* and it is the average number of incoming links or outgoing links per node.
[14] I found it is difficult to find a logistic regression solution for the result curves from simulations, because it is asymmetric. This might be a non-trivial issue, and needs further studies.

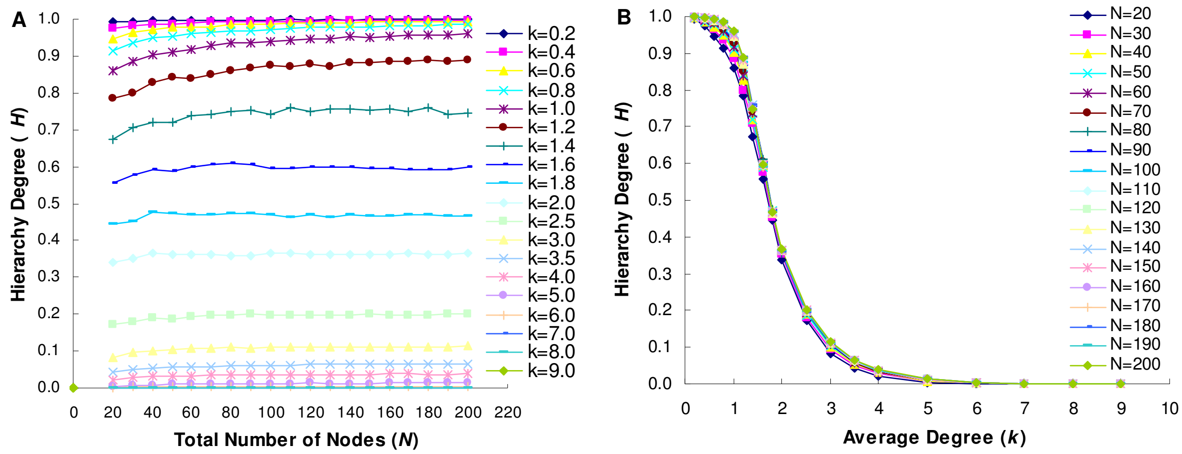

Figure 3.6 Hierarchy degrees of randomly-generated directed networks

Note: The value at each data point is the average of hierarchy degrees of 1,000 randomly-generated networks given the same n and k. Data points are connected by straight lines.

The result shows that the hierarchy degree is not necessarily zero for random networks. This indicates a potential kind of "white noise" hidden in hierarchy degree when it is expected to indicate the degree of having been structured of real-world networks. To avoid this kind of "noise", I further propose a metric, *z-score*, which quantifies how much a real-world network deviates from its comparable (benchmarking) random network in terms of flow hierarchy, expressed in units of the standard deviation of the hierarchy degrees of the random networks:

$$z = \frac{h_{real} - \hat{h}_{rand}}{\sigma_{rand}} \quad (3\text{-}5)$$

where h_{real} is the hierarchy degree of the empirical network, and $\hat{h}_{rand}$ and σ_{rand} are the average and standard deviation of the hierarchy degrees of an ensemble of random networks with the same n and m (or k) of the empirical network. The larger the value of z, the more the structure of the network deviates from randomness.

I calculated the hierarchy metrics of a diverse set of empirical evolving self-organizing networks, and compared them to those of comparable Poisson random networks with the same numbers of nodes (*n*) and links (*m*), with a focus on *z*-score. The results show that the chosen ecological, neurobiological, economic and information processing networks all exhibit stronger hierarchical architectures than their comparable random networks (see appendix B), indicating the emergence of flow hierarchy as a significant feature of real-world evolving self-organizing networks[15]. In section 3.6, I will show the specific application of the metrics to industrial network analyses.

3.5 Transaction Breadth Metric

Another aspect of network structure that has an impact on the flow hierarchy in industry architecture is how densely the firms are connected to each other. To quantify this factor, I define the average number of transactional relationships per firm in a sector as "transaction breadth", and denote it as "k". It is the same as average nodal degree in the network analysis field. In a network with n firms and m transactional relationships, $k=m/n$. In this section, we will explain what the transaction breadth parameter economically represents.

In a fully connected[16] industrial network of n firms, the lowest possible k arises when the "in-degree" or "out-degree" of each firm equals one. In this case, $k=(n-1)/n$. For example, suppose each supplier can only supply one customer, the transaction network is a top-down

[15] This technique presented here also makes it possible to objectively compare the hierarchies of different networks and of different evolutionary stages of a single network, and compare evolving patterns of different networks. We further discovered that hierarchy degree has increased over the course of the evolution of Linux kernels, confirming an early hypothesis by Herbert Simon (1962) on the emergence of hierarchy in evolutionary processes. For details, please see Appendix B.

[16] By "fully connected", I mean there are no isolated nodes without connections to any other nodes, rather than

tree (example shown in Figure 3.7A). There are *n*-1 links and *n* firms, thus *k*= (*n*-1)/*n*. If any link is broken, the network will no longer be fully connected. Similarly, if each customer firm can only purchase from one supplier, the network will be a bottom-up tree (example shown in Figure 3.7B), and *k* must also equal (*n*-1)/*n*. In the extreme where each supplier has only one customer and each customer has only one supplier, the network will be a pure line (example shown in Figure 3.7C), and *k* is still equal to (*n*-1)/*n.*

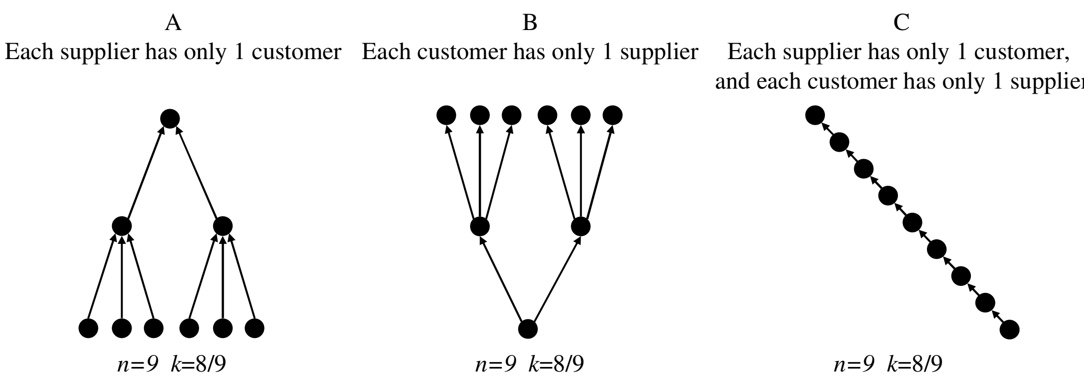

Figure 3.7 Non-market scenarios

In these three scenarios, the potential freedom of market transactions is not fully utilized by firms: either the suppliers or the customers, or both, are "captive" to the firms to which they sell or from which they buy. Extra linkages cause the network to deviate from the pure "tree" structures in Figure 3.7, and will at the same time cause *k* to be larger than (*n*-1)/*n*. Hence, the transaction breadth metric (*k=m/n*) captures the extent to which an industrial sector contains "true" markets, with firms buying from and selling to several others as opposed to captive supplier or customer arrangements.

3.6 Data and Empirical Measurements

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the sense that every node is connected to every other node.

In our exploratory study, I measured hierarchy (h) and transaction breadth (k) for two industrial sectors: the Japanese electronics production sector in 1993, and the Japanese automotive production sector in 1983, 1993 and 2001.

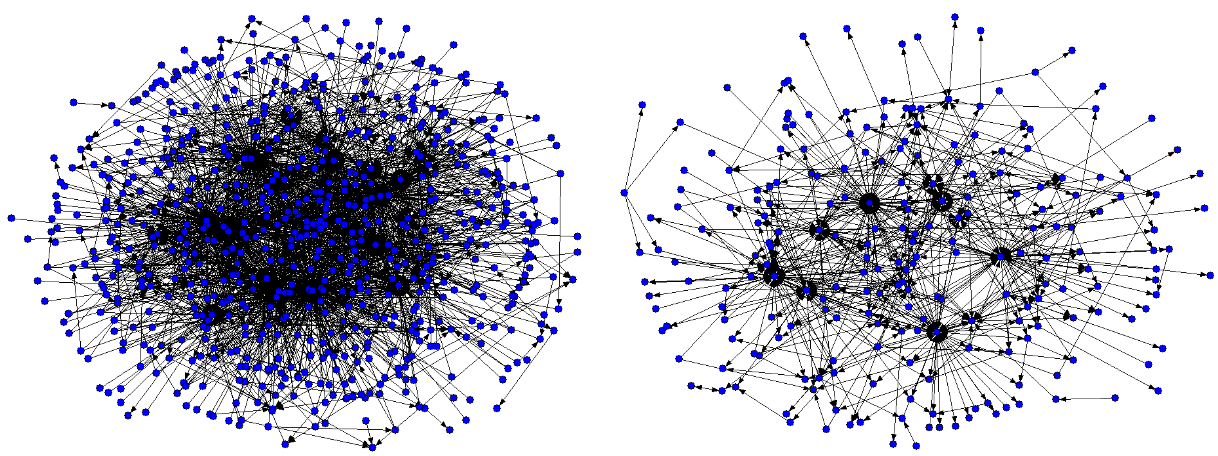
3.6.1 Data

I extracted the supplier-customer transactional relationship data from the series data books "*The Structure of Japanese Auto Part Industry*" and "*The Structure of Japanese Electronics Industry*" based on regular surveys by Dodwell Marketing Consultants. The company directories in these two data books provide the information on the major customers and suppliers for each firm. Such information makes it possible to extract "who-supplies-whom" type of connections, and to build multi-tier sectoral supply networks. The data books are only available in hard copy form, and had to be manually entered into an electronic database. I used the data books published in 1983, 1993, and 2001, but believe the data represents actually the scenarios in 2~3 years before the publishing year because the publications were refreshed every 2~3 years.

3.6.2 Results and Analysis

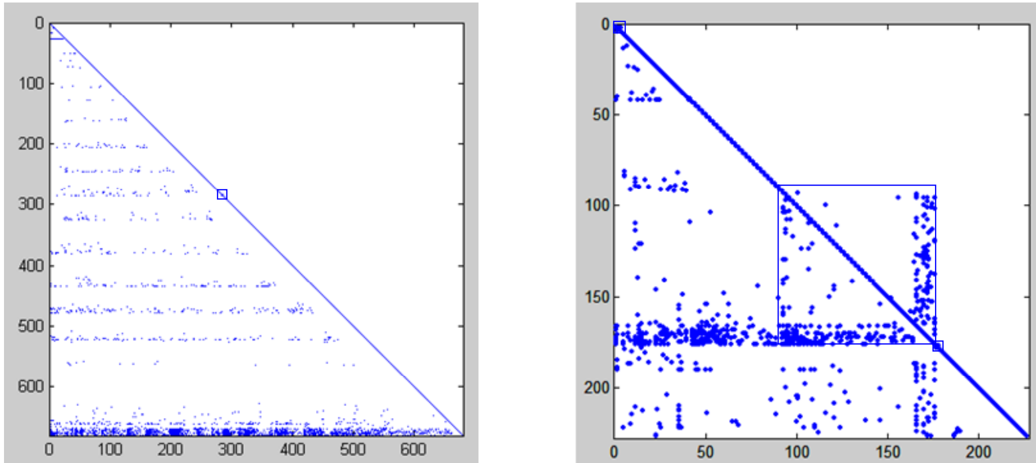
For each industrial sector at a specific year, I constructed a directed network, in which nodes are manufacturing firms and links are supplier-customer transactional relationships. For instance, if company A sells a product to company B, there is an arrow from A to B in the network. The transactions indicated are compensated transactions of physical products, excluding services and intellectual property.

Figure 3.8 shows the supplier-customer supply relationship networks of the automotive and electronics industry sectors in a comparable year (1993), based upon our empirical data and visualized using the software NetDraw. As in Figure 3.8 and Figure 3.2, network visualization is limited to capture the difference in hierarchy degrees of complex networks. In contrast, Dependency Structure Matrix (DSM) may be a better tool to visualize the difference in flow hierarchy embededness in complex networks. Figure 3.9 demonstrates a DSM representation for each of the two sectors shown in Figure 3.8.



A) Automotive Sector B) Electronics Sector

Figure 3.8 Network representations of Japanese sectoral supply networks in 1993



A) Automotive Sector B) Electronics Sector

Figure 3.9 Dependency Structure Matrices for Japanese sectoral supply networks in 1993.

Note: The elements on the axis are firms, and the dots are dependencies. For example, if company *i* is a customer of company *j*, i.e. company *i* depends on company *j*, we put a dot in the cell (*i*, *j*) of the matrix. Essentially, Dependency Structure Matrix is the transpose of the Supply Structure Matrix[17]. The matrix can be mutated differently by arranging the elements on the axis in different ways. In the two DSMs above, the firms are ordered using an algorithm from MacCormack, Rusnak and Baldwin (2006), and the firms mutually connected by cycles directly or indirectly are grouped together[18]. In general, if there are many cycles in a network, there will always be many dots above the diagonal. If a network is purely hierarchical, by mutating the matrix we may find at least one DSM layout, in which there is no dot above the main diagonal[19]. In addition, please note that the horizontal stripes showing up in the DSMs are unintended by-products of the algorithm we used. Further research is needed to explain them.

Table 3.1 summarizes the network descriptive statistics of the compiled network data, as well as the calculated transaction breadth (k), hierarchy (h) and z-score for respective sector networks. The comparison of the two sector data in one year (1993) shows that, despite its higher transaction breadth, the automotive production sector is quantitatively much more

[17] In a "Supply Structure Matrix (SSM)", if company *i* is a supplier of company *j*, i.e. company *i* supplies to company *j*, we put a dot in the cell (*i*, *j*) of the matrix, SSM.

[18] I thank John Rusnak of Harvard Business School for his technical assistance to produce the DSM figures.

[19] We may compare the hierarchy degrees of networks according to the DSM layouts mutated to such an extreme situation: the number of dots (dependencies) below the main diagonal is maximized and the number of dots above the main diagonal is minimized. Then, a flow hierarchy degree can be potentially calculated as the ratio of the number of dots below the main diagonal over the total number of dots. This ratio is equivalent to the alternative hierarchy metric defined in Appendix A.3, based on the Max [Longest] level-ranking algorithm. As in calculating that metric, finding such an extreme DSM layout of a network can be computationally complex and difficult.

hierarchical (0.9988) than the electronics production sector (0.5957). In addition, the hierarchy degrees of the automotive sector in Japan did not change much and remained high from the early 1980s to the early 2000s. The results on *z-score* confirm the same difference in the hierarchy degrees of the two sectors.

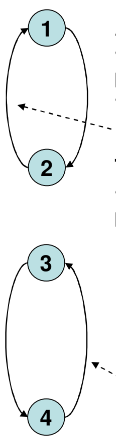
In particular, since a low k may promote hierarchy according to our learning from the random networks (Figure 3.6B), one can deduce there must be hidden mechanisms that drive down h in the electronic sector, because the electronics sector has a lower k and nonetheless a substantially lower h than the automotive sector. The model to be presented in Chapter 4 will address the unexplored mechanisms.

Table 3.1 Empirical Measurement Results

Network Attributes	**Japanese Automotive Production Sector**			**Japanese Electronics Production Sector**
Time	1983	1993	2001	1993
Number of Firms (n)	356	679	627	227
Number of Transactional Relationships (m)	1480	2437	2175	648
Transaction Breadth (k)	4.157	3.589	3.469	2.855
Hierarchy Degree (h_{real})	0.9973	0.9988	0.9991	0.5957
Average Hierarchy Degree of Random Network ($\hat{h}_{rand}$)	0.03160	0.0601	0.0684	0.1338
z-score (z)	89.53	82.34	75.06	14.90
Cycle Tracking	Two 2-node cycles	one 3-node cycles	one 2-node cycle	many

In fact, only one or two small supply cycles were found in the automotive industrial networks from 1983 to 2001. Figure 3.10 shows all the supply cycles found in the automotive industrial networks of different years. Particularly, according to the data, the transaction links included in the found cycles involved only minor volumes, and some of them disappeared later so that these cycles did not last long. For instance, in the 2000s, Toyota Auto Body acquired the other two firms involved in the only cycle found in the 1993 industrial network, so that the cycle no longer existed. In general, the automotive sector network is highly hierarchical.

A) The only two supply cycles found in 1983



Arakawa Auto Body (Araco)
• Major products" car assembly (trucks, buses, specialized vehicles, etc) 46%, interior parts 28%, other auto parts 6%, other items 20%
• This company changed its name to "Araco" in the early 1990s

This link disappeared after 1983

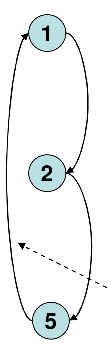
Toyota Auto Body
• Major products: car assembly 84%, (passenger cars 45%, commercial vehicles 31%, trucks 8%), auto parts, etc. 16%

Fuji Kiko
• Major products: steering columns, safety belts, transmission parts, pedals, engine parts, reclining seat equipment, suspension system parts, etc. 99%, agricultural machinery parts, other items 1%

This link disappeared after 1983

Ikeda Bussan
• Major products: seating 78.3%, interior accessories 14.4%, chemical products 6%, other items 1.3%

B) The only supply cycle found in 1993



Araco
• Major products: vehicle Assembly (trucks, buses, specialty vehicles, etc) 50%, Seating, door trims, and roof linings (50%)
• Customers: Toyota 98.4%, Daihatsu motor 0.2%, Toyota Auto Body 0.1%

Toyota Auto Body
• Major products: car assembly 84%, (passenger cars 45%, commercial vehicles 31%, trucks 8%), auto parts, etc. 16%
• Customers: Toyota Motor, Toyota Tsusho, Gifu Auto Body Industry

This link disappeared after 1993

Gifu Auto Body Industry
• Major products: bodies for trucks, specialty vehicles 64%, pressed auto parts (seat adjuster, radiator baffles, door trims) 31%, others, 5%
• Customers: Toyota Motor 90%, Takashimaya Nippatsu Kogyo 3%, Toyota Shatai 1%, Dahatsu Motor 1%, Araco

Toyota Auto Body Co Ltd (TA) acquired the vehicle manufacturing and sales business of Araco Corp (AR), a manufacturer of automotive seat cover, and a unit of Toyota Motor Corp (TM) – Announced on Oct 01, 2004

Toyota Auto Body Co Ltd (TA) acquired the remaining 89.09% interest of Gifu Auto Body Co Ltd, a manufacturer of automobile and truck bodies – announced on Oct 01, 2007

C) The only supply cycle found in 2001

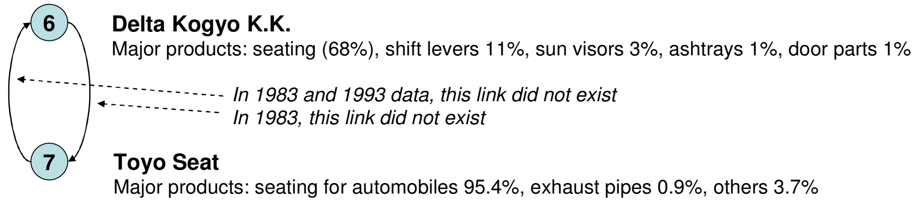
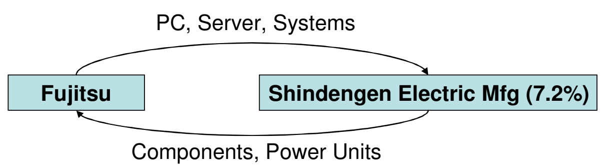


Figure 3.10 All the supply cycles found in the automotive sector supply networks

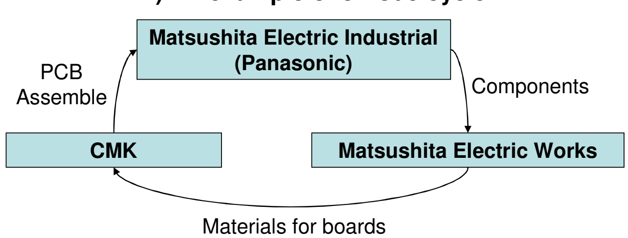
Thus the direction of "upstream" and "downstream" is very clear in the automotive sector, and there are almost no "backward-flowing" transactional relationships. In contrast, 40% of the transactional relationships in the electronics sector in 1993 are part of a cycle. In Figure 3.11, I show two real examples extracted from the network data. There are 51 two-node cycles and many larger cycles. Most of the cycles include a diversified conglomerate electronics firm, such as Panasonic and Fujitsu[20].

A) An example of 2-node cycle



Note: the percentage provided in the parentheses was the stake of each company owned by Fujitsu. The information on what was transacted is based on the guesses of the interviewee at the company based on his historical/domain knowledge on the firm's business in the early 1990s.

B) An example of 3-node cycle



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[20] I tested and found only 7 two-node cycles left after removing the largest 10 firms (by revenue) from the network. In the new network without the top 10 firms, 14 out of 221 links are on cycles, i.e. h=0.9367.

Figure 3.11 Example supply cycles in the electronics sector supply network

Therefore, in the electronics sector it is not clear which firms are "upstream" and which are "downstream". The sector is closer to a bazaar or pure market in which any firm may buy from any other firm. This low degree of hierarchy in the electronics provides a counter case against the Nakano and White hypothesis (2007) that assume directed acyclic graph (DAG) is a general property of production networks of firms.

In addition, the significant difference in the degree of hierarchy in the two sectors in Japan also raises questions concerning the argument stressing the impact of the Keiretsu culture on the hierarchical relationships between firms in Japan. Though many of the suppliers firms are Keiretsu members of the largest assemblers in both sectors, cycles took place among Keiretsu firms in the electronics sector, but not in the automotive sector. By expanding the analysis from pairs of firms to the overall network, and from the focus of one industry sector to the comparison of multiple sectors, we are able to see this difference in industrial hierarchy in the two sectors in both of which the Keiretsu relationships are evident (Womack, Jones and Roos, 1990; Paprzycki, 2005).

3.7 Chapter Summary

In this chapter, I developed a network-based metric and algorithm to measure the degree of hierarchy in transactional relationships among firms, and applied it to the transaction data from the two industrial sectors in Japan. The empirical results show that the electronics sector exhibits a significantly lower degree of hierarchy than the automotive sector due to the presence of many transaction cycles. This quantitative evidence on the degree of hierarchy challenges the existing assumption of the hierarchical relationships among firms in industry sectors. The next sections aim to provide an explanation to the observed difference in hierarchy degrees of the two sectors.

Chapter 4

Modeling Hierarchy in Industry Architecture

> *"Mathematical modeling is about rules - the rules of reality…But a piece of the real world encoded into a set of mathematical rules (i.e. a model) is itself an abstraction drawn from the deeper realm of 'the real thing'".*
>
> -- John Casti

In this chapter, I present a model that integrates the spirits of abstraction and comprehensibility. The model is used to link the results obtained at the sector level to new understanding at the firm level.

4.1 Modeling Motivation

Different industrial sectors may exhibit different architectures, and a single industrial sector's architecture also changes as it evolves. In Chapter 3, I have empirically calculated the hierarchy degrees and transaction breadths of two different industrial networks, and observed their differences. The two inductive cases (Eisenhardt, 1989) allow new insights on the hierarchies of industrial sectors, and a further research question -- how does the hierarchy in industry architecture arise and change? However, the sample of two sectors is limited in terms of the industrial diversity and time period covered to answer such a question. A formal theory on the hierarchy in industry architecture is still in infancy.

This chapter aims to construct a formal model (Freese, 1980) to describe industrial sectors with random networks, in order to understand how industry hierarchy emerges from the transactional interactions of individual firms. The central purpose and value of this model is not to test a previously-proposed theory, using traditional multivariate statistical techniques (Pfeffer, 1993) which lacks conceptual precisions and logical theoretical arguments (Sutton and Staw, 1995; Davis, 2007), but to elaborate the theoretical constructs and logic, explore what emerges from them, and then create instructive theoretical propositions, prior to further empirical tests.

4.2 Literature Review: Analytical Network Models

In the network analysis literature, there has been a major strand that aims to build and manipulate mathematical network-construction models in order to derive insights on network-wide properties as emergence of the interactions of individual network agents. The models are often built to theorize the existing understanding of the mechanisms or rules that underlie the observed phenomena from empirical research, such as local clustering and random linking of the small world phenomenon, and preferential attachment of the power-law degree distribution in networks, etc. Some of these models are mathematically complex so that simulations are often required to obtain derivatives and deliver insights. The model introduced in this chapter is also in this tradition. In the following, I first review the major network models in the literature, and then introduce my model.

Watts and Strogatz (1998) explored a one-dimensional 'ring' model of networks that can be tuned by random rewiring between regular networks and pure random networks. By simulations, they found that some networks generated in the middle ground (with certain degree of controlled disorder) can be highly clustered, yet have small characteristic path lengths. They call this class of networks with such coupled characteristics "small-world networks'. This tunable model provided a way to interpret the small-world phenomenon (Milgram, 1967; Kochen, 1989), i.e. six degree of separation (Guare, 1990; Watts, 2003).

The power-law degree distribution existing in a number of networks has also led to modeling efforts aimed at explaining its origins. Some years later than Price's empirical paper (1965) on the power law degree distribution of the citation network of scientific papers, Price (1976) published another paper that used the "*accumulative advantage*" process model to explain how the networks with "power law" form. The basic mechanism is that the new nodes are connected to the existing nodes, with the likelihood proportional to the degree of the target node.

In fact, Price's model was built upon the early idea "*the rich get richer*" from Herbert Simon (1955), when he was researching wealth distributions, rather than networked systems. In sociology, a similar concept is often referred as the "*Matthew Effect*" (Merton, 1968). Price's contribution is that he took the idea of Simon and applied it to network systems. After him, there have been many varied forms of the Price's model, on which Newman provided a comprehensive review (2003).

Although Price's model appears to be the first and still the most accepted explanation for the power-law degree distribution observed in a variety of networks, it is largely unknown in the scientific community until Barabasi and Albert (1999) rediscovered it and coined the term "*preferential attachment*". The paper of Barabasi and Albert (1999) led to an explosion of empirical research on power-law distributions and mechanism models varied from Price's (1978). What they did was simplifying Price's model by ignoring the directions of linkages.

Recently, a few mathematical models that construct hierarchical networks (of different kinds) are proposed and used to explore the emergent properties or functional performances of networks constructed differently. For instance, Ravasz and Barabasi (2003) proposed a model to construct nested hierarchical networks that combine the "scale-free" property with a high degree of clustering[21] simultaneously. Most importantly, the degree of clustering following a strict scaling law $C(k) \sim k^{-\beta}$, i.e. the clustering coefficient of a node is dependent on its degree. In contrast, this scaling law does not apply to other traditional network models, including the scale-free model (Barabasi and Albert, 1999), random network model (Erdos and Renyi, 1959; Bollobas, 2001), and the small-world model (Watts and Strogatz, 1998).

[21] They started with a small cluster of n densely linked nodes. Next, they generated n-1 replicas of the hypothetical module and connect the n-1 external nodes of the replicated modules to the central node of the old module, obtaining an n^2-node network. Subsequently, they again generated n-1 replicas of this n^2-node network, and connect the $(n-1)^2$ external nodes to the central node of the original module, obtaining a new network of n^3 nodes. Such replication and connection steps can be repeated indefinitely, and the number of nodes of the network is increased by a factor n in each step. They also showed a stochastic version, in which only a p^k fraction of the newly added nodes are randomly picked and connected to the nodes belonging to the central module in iteration k. p is the probability variable in the range of 0 and 1. Preferential attachment rule is used to decide which central node the randomly chosen new nodes are linked to (Ravasz and Barabasi, 2003).

They further conjectured that this scaling law quantifies the coexistence of a hierarchy of nodes, and proposed it as an indicator of the presence of a hierarchical organization in real networks.

Dodds, Watts and Sabel (2003) constructed a simple model of organizational networks where links are randomly added to a hierarchical backbone, in order to explore the correlations between the varied network structures and functional performances for information exchanges, under different conditions. The hierarchical backbone is a tree determined by the number of levels and the branching ratio at each level. By simulations using this model, they identified a class of "multiscale" networks, in which the individual nodes, as well as the network as a whole, are robust to system failures related to information congestion.

Flow hierarchy is an essential feature of food webs, and a number of mathematical network construction models have been developed in order to replicate actual food webs. The cascade model (Cohen, 1998) orders species along a directed axis randomly, and each species chooses prey randomly only from the species who are positioned lower than itself on the axis. Networks generated this way are purely hierarchical as they exclude cannibalism or feeding cycles. The niche model (Williams and Martinez, 2000) distributes the feeding connections of a predator into its "niche" range, whose center is placed lower than the predator's position on the hierarchy axis. Although feeding cycles are possible, the resulting networks are always interval, that is, all the prey of a predator are consecutive on the hierarchy axis. In the nested hierarchy model (Cattin, 2004), closely related predators tend to share their prey (to consider the phylogenetic constraint), with occasional departures (to consider the adaptations to new environments and new prey). These models have stimulated a number of variants (Stouffer, 2006; Allesina 2008; Willams and Martinez, 2008).

In general, food web models aim to replicate a target actual food web, given the information on network size (i.e. numbers of nodes and links), because food webs are normally assumed to be scale-dependent (Martinez 1993, 1994; Dunne et al, 2004). The goodness of fit of a model is often tested by comparing a number of structural properties of the model-generated networks and the targeted empirical network (Williams and Martinez, 2008). Then, a "good" model is utilized for the exploration and prediction of more complex properties of food webs such as stability, robustness, etc (Dunne et al, 2004).

In our pursuit of a model for networks with embedded flow hierarchies, the networks are neither necessarily scale-dependent, nor required to replicate a real world network, but expected to be used to explore the mechanisms on how flow hierarchies form and change.

4.3 Model Description

4.3.1 Basic Rules

Industry architecture is essentially the collective result of the decisions and behaviors of individual firms on their transactional links with each other. Thus, my model is designed to relate the sector-level architectural pattern, i.e. hierarchy, to micro patterns of connection at the level of individual firms, and to analyze how firm-level factors may interact and lead to different degrees of hierarchy in an industrial sector. The existing literature on firm behaviors and market structures has provided a solid ground and inspirations for such a formal model (Weick, 1989; Davis, 2007) to build upon. Specifically, the industrial network model to be introduced builds on three idealized mechanisms or rules of market structures:

1) The mapping relationship between roles and positions of networked firms (White et al., 1976; Wasserman and Faust, 1994): a firm is situated in its position within the network of firms according to its role.
2) Niche (Burt and Talmud, 1993; Podolny at al, 1996; White, 2002b): a subset of firms which are similar in terms what they buy and what they sell, i.e. roles. Firms taking the same role in a production process are situated in the same niche of the network of firms.
3) Hierarchy (Coase, 1937; Simon, 1962; White, 2002a): for specialization and organizational learning, firms take technologically specialized roles institutionalized according to the sequential (i.e. hierarchical) stages of the production processes. So firms are situated into hierarchically-organized niches of a production network.

If the three rules are fully in place in a production sector, ideally one can construct an industrial network by connecting each firm to the firms in a niche downstream to it on the production hierarchy. However, real-world industrial networks are complex, and the three rules are often not fully satisfied. The model to be introduced is designed to comprehend such complexities.

Using this model, what we will look for is not idealized networks, or a single kind of industrial networks, but in the spirit of universality, a class of networks, each of which might differ in detail from all the others. By tuning parameters (representing important mechanisms), I will generate a wide spectrum of industrial networks and explore their architectures, in order to expand our understanding from limited empirical cases and thus shed light on the regularities that exist in the changes and variations of industry architectures.

4.3.2 Variables

Technically, this model describes how the hierarchy (*h*) of an industrial network, as the dependent variable, may be collectively determined by three causal variables:

1) ***n* (Network Size, i.e. Market Size)**: the total number of firms connected in the network.
2) ***k* (Transaction Breadth)**: the average number of unique customers each firm has[22]. It is empirically measurable, and is the same as *k* in the NK framework (Kauffman, 1993; Rivkin and Siggelkow, 2002) and average nodal degree in network analysis and graph theory (Newman, 2003).
3) ***s* (Transaction Specificity)**: The degree to which a firm is captive to a specific niche of customers positioned closely in the industrial network.

Transaction specificity is the key of this model. In the model, it is quantified as the percentage of a firm's selling transactional relationships that fall within a (pre-defined) niche range downstream to the firm in the industry hierarchy. When transaction specificity is 1, all the customers of the firm are similar in terms what they sell and buy, so are located in a contiguous niche downstream to it in the hierarchy. When transaction specificity is less than 1, some of the customers are located outside the expected ideal niche downstream to the firm,

[22] It equals the average number of unique suppliers each firm has in a given network.

the main niche is no longer contiguous, or customers of the firm are now in multiple niches. In such cases, the niche and hierarchy rules are no longer strictly obeyed, so real-world complexities may be accommodated.

Defined and calculated this way, transaction specificity in fact represents the degree to which a particular firm fulfills a specific role in production market network (sector) (Wasserman and Faust, 1994; White et al, 1976) according to the similarity of its customers in terms of their value-chain positions in the sector network. Particularly, transaction specificity can be calculated and analyzed only if we expand the level of analysis on industrial transactions to the entire sector network.

Therefore, I generate random networks based upon three rules, using three input variables n, k, and s, and calculate the hierarchy degrees (h) of the generated networks, in order to discover the mathematical relationship between the degree of hierarchy, h, and the causal variables, n, k, s. This implies a function of hierarchy degree dependent on three independent variables.

$$h = f(n, k, s) \tag{4-1}$$

By inverting this relationship, we can infer transaction specificity (s) from the empirically measureable variables, n, k and h. Transaction specificity may indicate certain set of previously ignored issues related to the transaction strategies of single firms, which will be further studied through interviews and field work (see Chapter 5).

4.3.3 Network Simulation

- **Baseline (*s*=1): Hierarchical Niches**

For the initial development of the model, I first build a hierarchical network with $s = 1$. The network is constrained to have the same k as a random non-hierarchical network, or a given empirical network. Particularly, my hierarchical random network combines a market niche mechanism with a hierarchy mechanism.

I begin by creating an upstream/downstream relationship between firms in the network. To do this, I assign each of the n firms to a uniformly distributed random position (λ_i), along an axis ranging from zero to one. Zero is the farthest up stream that a firm can be; one is the farthest downstream. Consider a focal firm i with position value λ_i. The entire downstream interval for firm i has a length $(1-\lambda_i)$. Next, I define the firm's niche range, r_i, as the interval containing the firm's customers:

$$r_i = X\,(1-\lambda_i) \tag{4-2}$$

where X is a random variable between 0 and 1, and the probability distribution of X is firm-independent. The focal firm's customer niche range can be located anywhere downstream. The parameter b_i fixes the location of firm i's niche range by defining its left most point. b_i is assumed to be uniformly distributed between λ_i and $(1-r_i)$.

All these assumptions jointly ensure that, in our hierarchical random network each firm sells products only to the firms strictly downstream from it, and the niche range is smaller than (or equal to) the downstream interval (See Figure 4.1). Although randomly generated, the network displays strict hierarchy. There are no cycles.

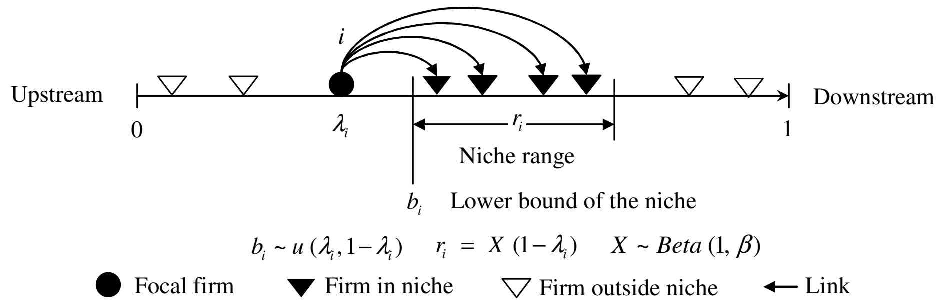

Figure 4.1 The hierarchical random network configuration

The model built to this step shares the perspective of Harrison White on the niches in production markets:

> *"Firms do indeed seek to maximize profits, but only as they find quality niches in recognized lines of business sustained as joint social constructions." (White, 2002a:xiii). "Only a niche within an industry establishes you in a line of business" [in the] "persistent directionality in continuing flows of intermediate goods"* (White, 2002b:87)

The niche range of a particular firm, r_i, is a random variable whose statistical properties are affected by the number of firms, *n*, and transaction breadth, *k*. First, the density of firms on the entire segment is *n*. Because the distribution of these firms is uniform, the expected number of firms in the niche of firm *i* is:

$$E(k_i) = nE(r_i) \tag{4-3}$$

For the entire system excluding the rightmost firm, the sum of the expected number of customers for each firm is:

$$E(m) = \sum_{i=1}^{n-1} E\,(k_i) = n\sum_{i=1}^{n-1} E\,(r_i) \qquad (4\text{-}4)$$

And, the expected average number of customers per firm is simply:

$$E(k) = \frac{E(m)}{n} = \sum_{i=1}^{n-1} E\,(r_i) = \sum_{i=1}^{n-1} E(1-\lambda_i)E\,(X) = \frac{(n-1)}{2}E(X) \qquad (4\text{-}5)$$

Thus, the random variable *X* is not only constrained to be between zero and one, but its expected value is

$$E(X) = \frac{2E(k)}{n-1} \qquad (4\text{-}6)$$

$E(k)$ is given as the input variable *k*, transaction breadth (average number of customers per firm, equal to average number of suppliers per firm). Note that, although k_i is firm-specific and randomly distributed in our model, *k* is an empirically measurable macro property of the network.

To generate an instance of a hierarchical random network, we need to choose an appropriate functional form for the distribution of *X*, and then impose the constraint of Equation (4-6). For computational ease, I use a beta-distribution with parameters (1, β) for the random variable *X*. This allows $E(X)$ to be in a computationally convenient form $1/(1+\beta)$. Given *k* and *n* as inputs, β will be determined by

$$\beta = \frac{n-1}{2k} - 1 \qquad (4\text{-}7)$$

Then a random niche range constrained by Equation (4-7) can be given to each of the aforementioned array of firms randomly located between zero and one. The focal firm is then linked to each firm in its niche range.

The hierarchical random network model suggests several non-trivial statistical properties of the generated networks:

(1) The model will create random directed networks whose *k* might not be equal but close to the input value.

(2) Firms close to, but to the left (upsream) of the rightmost (downstream) firm may have an empty niche range. This network in effect will have multiple top-tier assemblers, something that commonly occurs in practice.

(3) If a firm has an empty niche, and is not included in any other firm's niche, it becomes an isolate.

(4) Equation (4-2) indicates that, a firm's expected niche range is a decreasing function of the firm's position. In effect, downstream firms have fewer potential customers, hence average lower transaction breadth than upstream firms. Symmetrically, the upstream firms have fewer potential suppliers. This property makes our model different from other network models using constant *k* for each node (Watts and Strogatz, 1998; Woodard, 2006).

- **Hybrid (0<*s*<1): Random Rewiring**

I can generate a network that lies between the ideal types of random but fully hierarchical and fully random by "rewiring" some of the links in a hierarchical network, building upon the view that any complex systems are trade-offs of order (e.g. hierarchy in this study) and randomness (Watts, 1998; 2003). The extent of rewiring is determined by the parameter "transaction specificity (s)" and can be "tuned" between 0 and 1. Mathematically, s is the percentage of a firm's transactional relationships that fall within its (pre-defined) niche range.

When s is 1, all firms fulfill defined roles and the result is a hierarchical random network. At another extreme, when s is zero, all firms fulfill fully variable roles, transactional linkages are free to go anywhere, and the result is isomorphic to a pure random network. This means any firm may transact with any other firms, neither niche rule nor hierarchy rule applies, and k_i is no longer constrained by firm i's position. (Properties of such pure random networks are shown in section 4.3)

Between the two extremes, for the focal firm i, $s \cdot n \cdot r_i$ transaction links will be targeted at a specific group of firms and $(1-s) \cdot n \cdot r_i$ may go anywhere. Figure 4.2 demonstrates a hybrid configuration after rewiring. Cycles and backward links can emerge in the hybrid network.

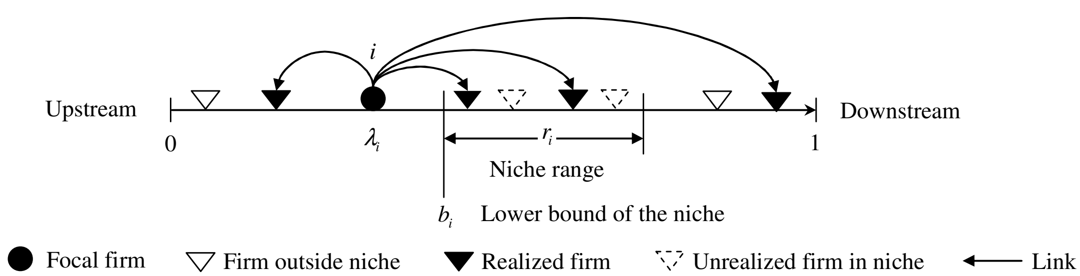

Figure 4.2 The mixture configuration after rewiring

The model allows the approximation for two realistic properties of a niche in the networks. First, it generates intervals inside a niche when $s < 1$, i.e., the discontinuity of a niche. More simply, a firm may not sell to all occupants of its downstream niche. Second, by random rewiring, it creates random linkages or adaptation effects, i.e., possible multiple niches, or a major niche plus several minor trials. Therefore, I name it the "***Adaptive Niche Model***" as it allows freedom for adaptive transactional relationships that deviate from pure hierarchy and niche rules. These are important transaction-related behaviors of firms, because they may be the firm's responses of competition dynamics in the sector, or be influenced by the nature of what are transacted. Chapter 5 and 6 will discuss these important issues.

By tuning transaction specificity parameter *s*, now I can generate a wide spectrum of industrial networks between two polar extremes[23]: hierarchical random networks with niches and random networks without hierarchy and niche embeddedness, weighted to one extreme or the other. Then we can examine the hierarchy degree not of a single industrial sector network, but of a whole class of networks, each of which differ in detail from all the others but nonetheless obey the structural rules established by *n*, *k*, and *s* and their relationships.

4.4 Simulation Results

The *Adaptive Niche Model* relates the network architectures to several independent variables, but the relationship is non-intuitive and the model is analytically intractable as it embeds the tension between structure and chaos (Davis, 2007). Thus, I choose to analyze the model by simulations. Simulation is relatively effective to reveal the non-intuitive correlation between the dependent variable (*h*) and independent variables (*n*, *k*, *s*), which is difficult to

[23] In doing so, we share the same spirit with Watts and Strogatz (1998) for modeling real-world network phenomena: "Ordinarily, the connection topology is assumed to be either completely regular or completely random. But many biological, technological and social networks lie somewhere between these two extremes."

uncover using other methods.

Although simulation is not new to engineers and economists, it has not been widely used in industry studies. In the field of network sciences, simulations have been widely used to analyze the properties of complex networks, largely because the network models are often highly mathematical (Newman, 2003). Our difficulties to analyze this industrial network model due to its mathematical complexity and the motivation for simulations are similar to those of Watts and Strogatz (1998), Dodds, Watts and Sabel (2003), and Woodard (2006), in their respective network analysis research.

Specifically, I use the Monte Carlo method (Metropolis and Ulam, 1949) to perform the *Adaptive Niche Model* and repeatedly simulate random networks with varied input parameters, and then compute the average hierarchy degrees of the controlled samples of networks. For each given combination of inputs (n, k, s), I simulate 2,000 networks, calculate the hierarchy degree for each and take the average. In order to improve the fitness of the generated hierarchical random networks, only the simulated networks with the given n firms fully connected and k within 3% of the target value were accepted as valid trials.

4.4.1 Impact of Network Size

Figure 4.3 shows the influence of network size (n) on average hierarchy degree (h) at various combinations of k and s. As introduced in section 3.4, h is calculated as the percentage of links that are not included in any cycle in a simulated network. The results show that hierarchy degree is essentially unaffected by changes in network size (n), when $n > 80$, regardless of s and k. Thus, when n >> 80 formula (4-1) can be simplified to,

$$h = f(k, s) \tag{4-8}$$

This means that we can use networks with a relatively small number of nodes (e.g. 100) to investigate the hierarchies of networks with a much larger number of nodes. Therefore, our later simulations use n=100.

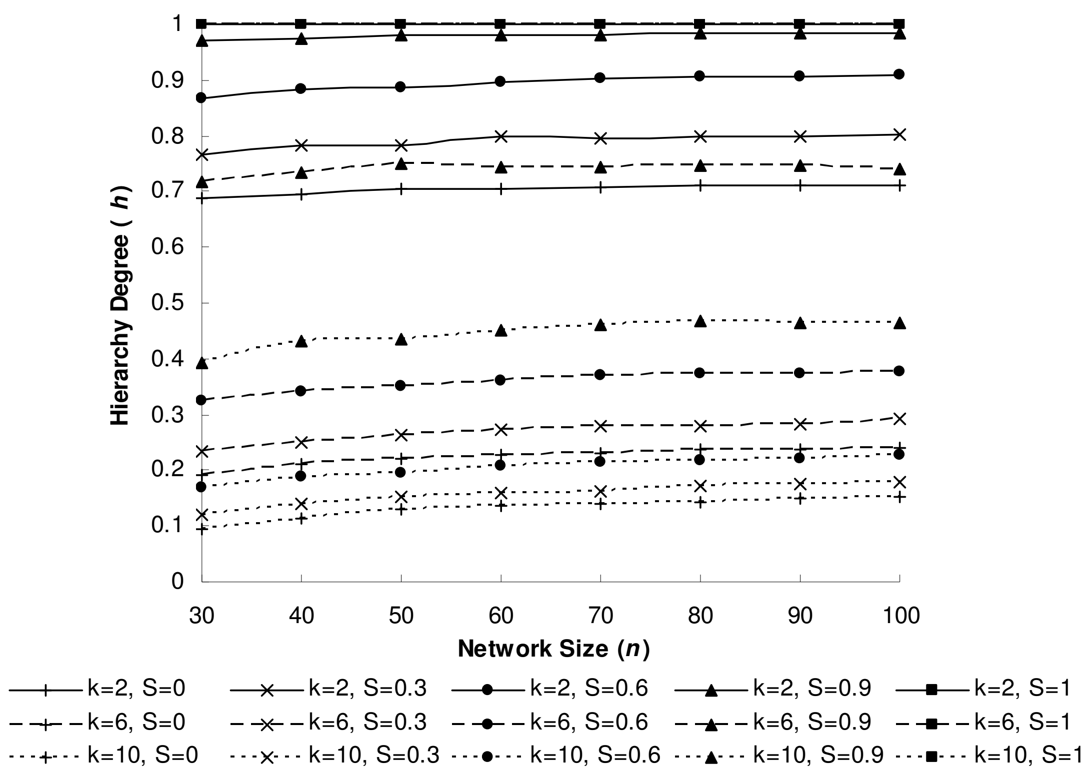

Figure 4.3 Impact of network size on hierarchy degree

4.4.2 Impact of Transaction Breadth

Figure 4.4 shows that hierarchy degree (h) decreases with transaction breadth (k) at various levels of transaction specificity, except s=1. When s is lower, h decreases more rapidly with the increase of *k*. When *s*=1, *h*=1 regardless of *k*, by definition. When *s*=0, then the networks generated are pure random networks, essentially determined by the given *n* and *k*. In particular, the result shows that hierarchy degree (*h*) for a purely randomly-wired network is not necessarily zero, depending only on *k*, when network size (*n*) is sufficiently large.

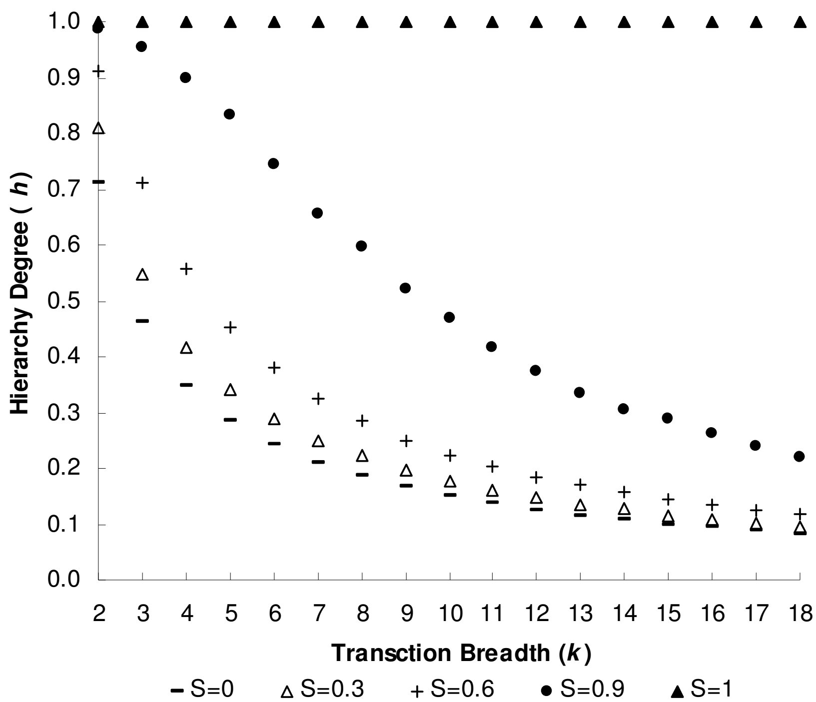

Figure 4.4 Impact of transaction breadth on hierarchy degree

4.4.3 Impact of Transaction Specificity

Figure 4.5 shows hierarchy degree (*h*) increases with transaction specificity (*s*) at different levels of *k*. When *s*=1, *h* equals 1 for all values of *k*. When *s*=0, hierarchy degree varies with *k*. The lower *k* is, the higher *h* is. When *k* is lower, *h* decreases more slowly with the decrease of *s*.

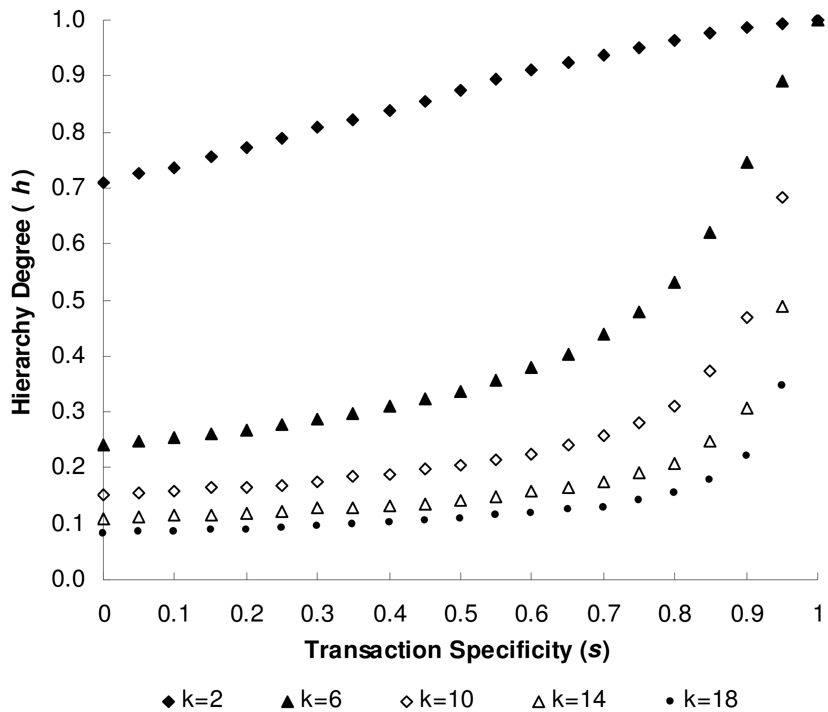

Figure 4.5 Influence of transaction specificity on hierarchy degree

Generally, transaction breadth (k) tends to pose a cap on the increase of hierarchy degree (h) driven by any potential increase in transaction specificity (s). This relationship for $h = f(k, s)$ is alternatively represented in a 3D figure and data table format in Appendix C.

4.5 Transaction Specificity

4.5.1 Inference

In particular, because h is monotonic with the changes in s and k, as shown in the results, the implicit function theorem ensures s can be associated with h and k by a single function, inverted from the results above. This can be described as the inverse function of formula (4-8),

$$s = f^{-1}(h, k) \tag{4-9}$$

Particularly, both *h* and *k* can be empirically measured when an actual network is given. Figure 4.6 demonstrates the process of inferring transaction specificity using the example of the Japanese electronics sector (n = 227 >> 80). Given the values of *h* (0.5957) and *k* (0.285), I infer its transaction specificity s = 0.3219.

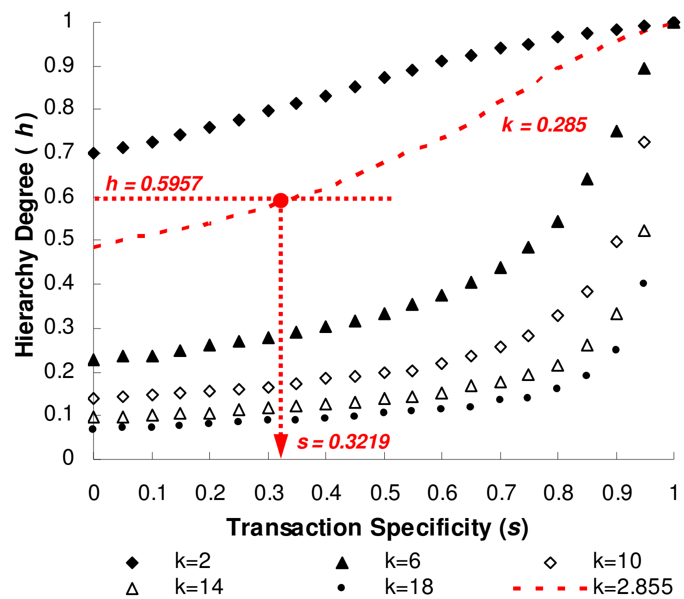

Figure 4.6 Example process of inferring transaction specificity

It follows that, in the context of this model of two micro-causal determinants of hierarchy, the automotive sector has a higher *s* than the electronics sector, because it has been empirically observed that the automotive sector has a higher *h* and a higher *k* than the electronics sector. By interpolating the empirically measured transaction breadth and hierarchy degree in Table 3.1 within the simulation results in Figures 4.4 and 4.5, I infer transaction specificity of the automotive sector is 0.9982, much higher than the transaction specificity of the electronics sector which is 0.3219, in the comparable year of 1993. In addition, the inferred transaction specificities of the automotive sector in 1983 and 2001 are respectively 0.9971 and 0.9985, essentially unchanged in 20 years.

To interpret the results from the theoretical analysis, I further conducted interviews with 3 automotive suppliers and 6 electronics firms in Japan in 2009, with a focus on the firms' strategic choices with regard to transaction relationships, and the related decision rationales of firms and the competition environments in the industrial sectors. The interview data qualitatively demonstrate the same difference in transaction patterns in the two sectors as in our measurement and model simulation analyses. The interview findings will be discussed in detail in next chapter.

4.5.2 Implications

In the foregoing sections, I have defined "Transaction Specificity" in the context of the industrial network model, and inferred its values for the empirical cases. In general network sciences, '*s*' is a mathematical variable that tunes networks between regular (hierarchy + niche) networks and pure random networks, and it can be termed 'Link Specificity'. As a matter of fact, the concept of transaction specificity indicates specific meanings in the fields of economic sociology, institutional economics, and engineering systems.

From an economic sociology perspective, each firm is situated in its position within the network of firms in a sector according to its roles. And, firms in production markets tend to take more fixed positions and roles than the actors in the financial markets (White, 2002a). However, there might also be variation of such tendency to fix position and roles. The creation of “Transaction Specificity” moves one step forward to quantify such a tendency of a firm to fix its roles as a degree between 0 and 1, which indicates the homogeneity of its customers (or suppliers) in terms of their relative network positions. The creation of the “Transaction Specificity (i.e. link specificity)” variable may open up new research opportunities to study the roles and positions of sociological interests.

In studies in the tradition of “new institutional economics” have largely focused on whether an external transaction or internal production is needed, with the neglect of where the transaction is oriented once given (i.e. upstream or downstream). Transaction cost approach has been the major method to study it. With “Transaction Specificity”, now we are able to quantify and measure where the transactions of a firm are oriented in the business eco-system, i.e. value co-creation network. In Chapter 6, I will show that transaction cost is still an important factor (among others, such as innovation dynamics) to consider in our socio-technical analysis to understand the different transaction specificities of different industry sectors and different types of transactions.

For research on industrial innovation and industry evolution, the quantification of transaction specificity provides a way to detect the evolution patterns of industries and products through possible fluid, transitional and specific phases (Abernathy and Utterback, 1978), and identify which stage an industry or product is in. With a better understanding on the evolutionary stage or status of an industry or product, a firm may adapt its strategies accordingly.

From an engineering system perspective, the transaction patterns of individual firms in aggregate determine industry architecture, and meanwhile are also influenced by more fundamental economic and technical forces. The concept of "Transaction Specificity" may bridge the gap between the understandings at the macro level of industry architecture and the micro level of product characteristics, so that potential socio-technical theories on how technology may affect the transaction strategy of single firms and overall industry architecture can be explored. Chapter 6 will further theoretically analyze the linkages between (inter-)organizations and product characteristics.

4.6 Chapter Summary

In this chapter, the *Adaptive Niche Model,* including the design of the tuning parameter -- transaction specificity, is created to relate the sector-level property – hierarchy – to two firm-level variables, transaction breadth and transaction specificity. It is the first model with random tunable networks to represent industrial networks. With the "*Adaptive Niche Model*" and the concept of "*Transaction Specificity*" developed in this thesis, we are now able to quantify where the transactions of a firm are oriented, and the tendency of firms to fix their roles and positions in industrial networks. The empirical measurement and model analysis together indicate that it is the low transaction specificity that drives down the degree of hierarchy in the electronics sector. The next Chapter will discuss and analyze the findings from the interviews with the industrial firms in Japan. The interviews were aimed at understanding the strategic transaction choices of individual firms and the underlying decision rationale, which underlie our previous measurement and modeling/simulation results.

Chapter 5

Observing Firm Boundaries and Transactions

"You can observe a lot just by watching."

-- Yogi Berra

In order to improve understanding of the results of the empirical and analytical analyses, link the findings to firms' strategies and decision rationales and constraints, and explore factors that the quantitative methods have limited ability to address, I visited and interviewed companies in the automotive and electronics sectors in Japan in 2009. In this chapter, I will describe, summarize, and analyze the findings from these interviews.

5.1 Interview Design

Field research, which is conducted by going to the firms and communicating directly with the managers and decision makers, offers a valuable complement to the research methods described to this point in the thesis, such as the statistical analysis of archival data, modeling, and simulation. Field research allows one to ask practitioners directly about their objectives and constraints, explore areas with little preexisting data or theory, facilitate use of the right data, and provide vivid images that promote intuition and inspiration (Helper, 2000). This dissertation has benefitted in these aspects from my fieldwork and interviews with Japanese industrial firms.

I visited and interviewed the executives of three automotive suppliers in Japan in March, 2009, five electronics manufacturing and technology companies in Japan in June, 2009, and another electronics company at MIT in January, 2010. I specifically chose firms in the two sectors analyzed in the foregoing chapters, in order to continue the comparison of the two sectors on a different level. I expected the interviews to shed light on the causes for, or uncover new phenomena that contradict, the learning from the data and modeling analysis.

Table 5.1 summarizes the firms and their characteristics in terms of what they buy and what they sell. I use pseudonyms for the companies due to confidentiality requests by the interviewed companies. The firms in each sector have different business specializations. The diversity of firm types on this list is representative to some extent of the value chains in both sectors in Japan. I visited only automotive suppliers for this study, not automotive assemblers (for example, Toyota, Nissan, etc), whose strategies have been well studied, with extensive literature and knowledge about them.

Most of the interviewees hold high-level positions, such as president, board member, director for procurement, and manager for corporate strategy. Their vision and experience made it possible to discuss not only day-to-day operations inside the company, but also corporate strategies and overall industrial environments and trends.

Table 5.1 Companies interviewed in the automotive and electronics sectors

Industry Sector	Firm	Firm Type	Interviewee	Selling Side		Buying Side	
				Products	Customers	Procurements	Suppliers
Auto	A	Material supplier	Manager for Planning	Metal, chemical, forged parts	OEM and system suppliers	Commodity; buy from commodity market, but know original sources	Raw material
	B	Tier-1 system supplier	Director for Global Procurement	Electrical, electronics, and mechanical systems	OEM	Specific; suppliers are required to design and produce specifically	Component and material
	C	Tier-1 system supplier	Procurement Coordinator (5 years of experience)	Electronics and electrical subsystems	OEM	60% Specific + 40% commodity; electronics purchases are non-specific	Component and material
Electronics	D	Diversified electronics corp.	Director for Global Procurement	Systems and components	Anyone *	Standardized components and parts	Anyone
	E	diversified electronics corp.	Director for Strategy	Systems and components	Anyone *	Standardized components and parts	Anyone
	F	diversified electronics corp.	Engineer	Systems and components	Anyone *	Standardized components and parts	Anyone
	G	mobile phone producer	Manager for Strategy	Mobile phones	Mobile carriers	Standardized components and parts	Anyone
	H	diversified electronics corp.	Past Board Member	Watch, printers, fax; components	Anyone, mostly int'l	Standardized components and parts	Anyone
	I	specialized supplier	President	Small parts, IC, etc	Anyone *	Raw materials	N/A

* Including affiliated suppliers, independent suppliers, and the component/device divisions of other diversified electronics corporations (even competitors).

The basic purpose of the interviews was to collect micro evidence on how firms behave in creating and managing the transactional linkages with their upstream suppliers and downstream customers, and the related incentives that underlie such transaction-related firm behaviors and strategies. Such inter-firm transaction behaviors and strategies are essential in this research, because in aggregate they determine industry architecture (as suggested in the industrial network model in Chapter 4). During the interviews, I asked questions about firm behaviors and discussed the motivators and constraints that the firm may or may not have considered in making decisions about products and technologies, such as the industrial and economic environments, the competitive landscape, company history and culture, etc. I also intended to lead our interviewees to think and talk about the underlying forces and fundamental rules that may impact their strategic decisions about who to sell to and who to buy from.

To achieve these purposes, I divided the interview questions into four broad categories:
1) Questions about procurement strategies and upstream suppliers. I asked about the firm's procurement portfolio (what to buy) and its pattern of purchasing linkages with its suppliers (whom to buy from). I also sought the decision rules (e.g., technology, cost) for the firm's strategic choices in procurements and relationships with suppliers.
2) Questions about product strategies and downstream customers. I asked about the firm's portfolio of products (what to sell) and its pattern of sale linkages with its customers (whom to sell to). I also sought the decision rules (e.g., technology, revenue) for the firm's strategic choices on products, innovation, and its relationships with customers.
3) General questions about how the company forms its procurement and product strategies. Broadly, the questions were about how the company manages organizational structure, procedures, and human resources to make these decisions.
4) General questions about the big picture, including industry structure, the competitive landscape, the industrial environment, etc, and how the firm's strategies address these issues.

Before analyzing the interview results, I first review the literature on strategies and organizational designs related to industrial transactions.

5.2 Firm Boundaries: Concept and Literature

Transaction activities take place on firm boundaries. Firm boundaries are the demarcation between a firm and its environment (Santos and Eisenhardt, 2005), and they are where the two interact. Every firm purchases inputs and sells its goods or services to intermediate and final markets via its boundaries (Coase, 1937). Otherwise, the firm is not counted as part of an economic system. The study of firm boundaries originated with the essay by Coase (1937) on why and when firms or organizations are preferred to markets. Coase's original idea was that internalizing some economic activities in the boundaries of firms may be more economical than conducting market transactions, when the costs of transaction due to imperfect information are relatively high.

In fact, firm boundary design has systemic impacts, more than transaction costs, on firm capabilities and performances (Jacobides and Winter 2005; Santos and Eisenhardt, 2005; Jacobides and Billinger, 2006). Furthermore, technical and economic motivators and constraints may affect the structure of firm boundaries. Firm boundaries may also be influenced by internal and external forces at the same time.

Essentially, a firm's boundary structure (i.e., what the firm does on the boundaries with the markets) may indicate transaction specificity, as well as, in the aggregate, industry architecture as discussed in Chapter 4. Therefore, firm boundary is the main place to observe phenomena of the interest to this research. This chapter seeks to understand the transaction-related activities of firms based on firm boundary theories, and explores the underlying rationales and rules.

I first consider the different kinds of boundaries of a corporation. According to Santos and

Eisenhardt (2005), the horizontal boundary is defined by the scope of products and markets addressed, while the vertical boundary is defined by the scope of activities undertaken in the industry value chain. Based on their definition, the horizontal boundary of a firm is the most downstream boundary by which the firm sells its final products, at least some of which have gone through all the value-adding stages covered by the firm. Here I extend to differentiate the downstream horizontal boundary and upstream horizontal boundary of a firm. The downstream horizontal boundary is defined as the same as the horizontal boundary by Santos and Eisenhardt (2005), while the upstream horizontal boundary is the most upstream boundary by which the firm procures inputs for its most upstream activities in the value adding process. The downstream and upstream horizontal boundaries of a conceptual firm are demonstrated in Figure 5.1.

Firms often operate on multiple stages of a value chain or value accumulation process. Some of the intermediate activities may also procure inputs from external suppliers, or sell the components or parts produced in house to intermediate industrial markets. Here I define the vertical boundary of a firm as where the firm buys intermediate inputs (e.g., components or parts) for integration at an intermediate value-adding stage higher than the most upstream stage it covers in house, and where the firm sells intermediate outputs (e.g. components or parts) produced at an intermediate in-house value-adding stage lower than the most downstream stage it operates in house. Vertical boundary is not at the most extreme of up or downstream within the firm. The vertical boundary of a conceptual firm is demonstrated in Figure 5.1.

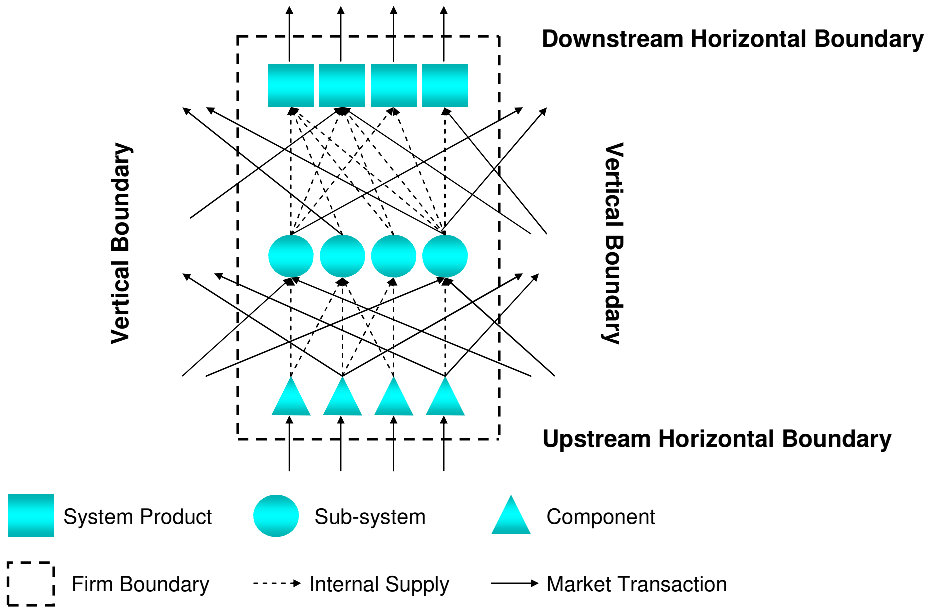

Figure 5.1 Horizontal and vertical boundaries of a conceptual firm

For a real example, Panasonic not only works on final system products, such as computers and TVs, but also electronic components used in these system products, as well as even more upstream and smaller parts. Thus, Panasonic sells computers and TVs via its downstream horizontal boundary, procures raw materials via its upstream horizontal boundary, and buys and sells electronics components via its vertical boundary. The later sections of this chapter and Chapter 5 will shed light on what makes it necessary or possible for Panasonic or other similar firms to do so.

5.2.1 Horizontal Boundary Design Choices

In designing its downstream horizontal boundary, a firm chooses mainly between concentration and diversification. Simply put, a firm may choose to concentrate on producing and selling one product or one type of product, or it may choose to diversify into the businesses of multiple (types of) products or services. Observation of the diversification of firms' downstream horizontal boundaries and analysis of the underlying rationales has a long history (Chandler, 1962; Teece, 1982; Teece, Rumelt, Dosi and Sidney, 1994). According to neoclassical microeconomics, downstream horizontal boundaries are simply determined by potential economies of scope. However, the gain from economies of scope may be neutralized by the governance costs associated with the indivisibility and nontradability of assets (Teece, 1982). Thus, downstream horizontal boundary design needs to consider governance costs (Santos and Eisenhardt, 2006).

There are two different designs of diversifications that a firm may choose: related diversification and conglomerate diversification (Teece, 1982; Rumelt, 1974). They imply different degrees of benefit and cost from economies of scope and the costs of governance. In related diversification, the diversified businesses or products require many physical and human assets in common, and these assets are coherent between the diverse activities. Governance costs are low and efficiency is high (Teece, 1982). Some diversified Japanese electronics firms, such as Fujitsu, can be characterized as following a related diversification strategy, because their distinct system products (PCs, mobile phones, TVs, etc) are in fact designed and developed using common knowledge of electronics, and can be manufactured in shareable production facilities.

Conglomerate diversification, in contrast, requires quite disparate physical and human assets. Whereas related diversification pursues strategic values in organizational and technological capabilities, the incentive for conglomerate diversification is often to access the financial values of disparate businesses operations and optimize the overall financial return of the entire portfolio of unrelated business operations. Companies like General Electric and Hitachi pursue a conglomerate diversification strategy. Their business activities span medical devices, energy, electronics, media, trains, etc, many of which share few production or development competencies but are financially complementary.

In general, a framework for understanding how a firm designs its downstream horizontal boundaries needs to include, but not be limited to, many systemic and interacting issues, such as economies of scope and scale, capacity and capability, organizational knowledge and learning, path dependencies, the industrial environment, and the nature of the products.

In addition, the decision of a firm on what value chain activities it operates simultaneously determines the location of the upstream horizontal boundary and the width of its vertical boundary. Thus, the upstream horizontal boundary design is closely related to the design of the vertical boundary, and is discussed together with the vertical boundary design choices in the following section.

5.2.2 Upstream Horizontal Boundary and Vertical Boundary Design Choices

Transaction cost economics (Coase, 1937; Williamson, 1985) has been the dominant tool in analyzing upstream horizontal boundary and vertical boundary decisions. Firms weight the benefits of internal production ("make") against the costs of using markets ("buy"), to make strategic choices about what activities should be done in house, i.e. where the upstream horizontal boundary is and how wide the vertical boundary is. However, transaction cost analysis only looks at the governance of one, or one set of, individual transactions. It does not consider the design of the boundaries of a firm as a whole, which may affect a firm's overall strategic and productive capabilities and long-term prospects. In reality, many (large) firms often conduct multiple types of transactions across their upstream horizontal boundaries or vertical boundaries, and thus transaction cost analysis is insufficient to explain the overall boundary design of a firm.

The design of the upstream horizontal boundaries and vertical boundaries may involve more complicated and systemic rationales than transaction cost (versus production cost), and needs to consider systemic factors that operate at the level of the entire corporation. Santos and Eisenhardt (2005) advocated that firm boundary research should engage a broader view than transaction cost economics and identified four boundary conceptions (efficiency, power, competence and identity) that may shape the boundary design of a firm.

In a simplest case, a firm, which operates on one or multiple value-adding stages, buys inputs via its upstream horizontal boundary, sells the outputs via its downstream horizontal boundary, and the vertical boundary is closed. That is, all the intermediate outputs are internally transferred and used by downstream activities inside the firm, and all the intermediate inputs are internally provided by upstream activities inside the firm.

In the past decade, some researchers have recognized some complex forms of vertical boundary activities. Jacobides and Billingers (2006) illustrated and defined an intermediate type of boundary design - a permeable vertical boundary. A permeable vertical boundary is partly integrated and partly open to the markets along a firm's value chain. That is, the firm can simultaneously make or buy intermediate inputs, and can transfer or sell intermediate outputs downstream. Permeability is an intermediate status between complete vertical integration and complete disintegration. Jacobides and Billingers used a single firm case to show how the permeable design of the firm's vertical boundary may affect capabilities and performance at the level of firm: improve transparency and monitoring, lead to greater efficiencies and more effective operations, affect capital allocation, support strategic objectives, facilitate innovation, and dynamically shape the firm. During my fieldwork in Japan, which I will discuss later in this chapter, I found that permeable vertical boundary designs are popular among electronics manufacturers in Japan.

Most existing research addresses either horizontal or vertical boundaries separately. In addition, most boundary design studies have focused on micro-economic factors and reasoning, neglecting the influences of the industrial environments outside the firm, such as resources and competition dynamics, as well as the influences of product architectures that affect innovation and production processes inside firms. My interviews were designed to explore these issues, and the interview results also shed light on fuzzy linkages between the horizontal and vertical boundary structures of manufacturing firms in Japan.

5.3 Interview Results

5.3.1 The Automotive Sector: Specificity in Products, Processes, and Transactions

- **Industrial Environment**

The automotive suppliers share a perception of their industry sector's industrial environment as saturated and slow-paced. They believe that it is difficult to achieve radical innovations in the automotive sector, and that incremental innovations are taking place slowly. They identify the risks for their companies as including: excess competition on price and quality, the loss of capability and incentive to innovate, and over-reliance on the pull of automotive customers. The R&D efforts of automotive supplier firms are mainly for sustaining and incrementally improving their traditional products and business. The competition in automotive-related business is centered on quality, cost, and delivery. The automotive suppliers I interviewed agree on that in the foreseeable future they will work on the same products while continuously improving their quality. They believe their business prospects will continuously rely on the needs of their automotive customers.

- **Strategic Responses: Specificity in Products, Processes, and Transactions**

Responding to these challenges, automotive suppliers' main strategies emphasize strengthening relationships and trust with their customers and suppliers by continuously improving their quality, cost, and delivery (QCD) through close collaboration with their customers. To improve quality and lower costs, they specifically tailor their product design and production process to ensure high-quality integration into the larger system products of their customers. Meanwhile, they also favor the specific design and production processes offered by their suppliers. A number of past studies have documented the Japanese automotive sector's collaborative efforts for QCD, at both plant level (Womack, Jones and Roos, 1990) and the inter-firm level (Dyer, 2000; Helper, MacDuffie and Sabel, 2000).

All of my interviewees in the automotive sector agree that trust and collaboration with customers and suppliers is essential to their business, but they also worry about being overly reliant on their customers. One interviewee said that since the economic recession began in 2008, there has been a risk that some of their lower-tier suppliers may go bankrupt before his company is paid by the automotive assembler customers and is able to finance the smaller and more vulnerable suppliers.

I found that automotive supplier firms I interviewed are either unwilling to diversify their product portfolios or incapable of creating radically new products for customers outside their main niches. This indicates high transaction specificity. One major automotive electrical and electronic systems supplier is unwilling to diversify its products and transactional relationships because of its previous failures with diversification. In the 1990s, this firm tried to use its know-how in electronics to enter the consumer electronics markets (e.g., LCDs, TVs). The expansion was unprofitable largely due to the firm's unfamiliarity with marketing and distribution channels. The firm returned to its concentration on automobiles. The interviewee told us that “the company’s DNA is automotive.”

Another automotive electronics supplier's dedication to tailored automotive needs has constrained its capacity to develop competitive not-for-automotive products. The interviewee from this company told us that their product development team is accustomed to the integral designs and slow pace of the automotive business, which makes them incapable of developing competitive components in the dynamic consumer electronics sector. For them, investing in collaborations with business partners to improve QCD is more valuable and meaningful than investing in innovations for new products for new customers. This may indicate the rising asset specificity of this firm due to the specific needs of its automotive customers.

- **Firm Boundaries**

Not only automotive suppliers but also automotive assemblers are specific, and trying to become more specific, about their products, processes, and customers. Most manufacturers in the automotive sector focus primarily on automobiles on their downstream horizontal boundaries. On the vertical boundaries, previously research has found that Japanese automotive assemblers normally produce certain components and parts while procuring some other components and parts from outside suppliers (Nobeoka, 1996). Sometimes, integrators produce in-house and procure externally the same or similar components (Parmigiani, 2007). However, it is seldom observed that the automotive assemblers sell their internally designed and produced components and parts to other assemblers or suppliers.

Figure 5.2 demonstrates a case similar to what is happening in the automotive value chains. Automotive assemblers may concurrently produce and procure components and parts, but they normally do not sell components and parts via their vertical boundaries to the intermediate industrial markets[24].

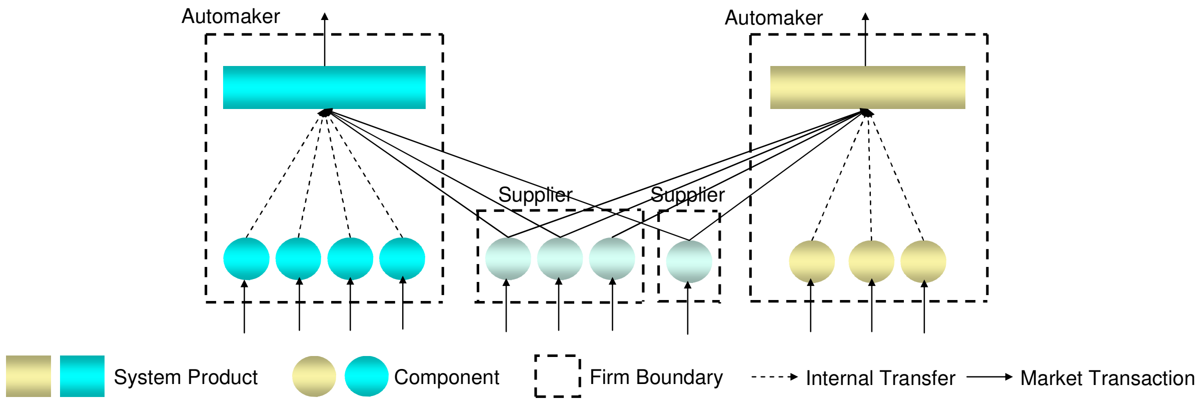

Figure 5.2 A schematic representation of the transactions on the horizontal and vertical boundaries of automotive manufacturers

In general, the automotive sector's lack of radical innovation mechanisms and its managerial perception of the maturity of the industry sector intensify competition on QCD and drive firms to product designs and processes that are specific to their long-time customers. This creates a reinforcing loop with the lack of incentive and capability to develop new products for new customers, which further locks supplier firms into their positions in the sector's hierarchy: its sequence of assembling automobiles from raw materials to components and parts, sub-systems, and entire vehicles. The purchasing and sales transactions of a company tend to follow a regular direction from lower tiers to higher tiers.

- **Perception of Tiered Industry Architecture**

Automotive suppliers view the automotive supply network as a tiered architecture and

[24] An exception is the former Saginaw division of General Motors, which sold steering and drive train components to other automobile manufacturers than GM at the same time of supplying nearly all of GM’s needs.

perceive no examples of transaction cycles or of non-hierarchical transactional relationships (i.e., transactions in which a higher-tier company supplies a lower-tier company)[25]. They attribute this perception of "being well organized," or of having hierarchical regularity in transactional links, to the maturity of the current automotive industry.

5.3.2 The Electronics Sector: Persistent Dynamics in Products and Transactions

- **Industrial Environment**

The electronics firms I interviewed shared the perception that the industrial environment of their industry sectors is highly dynamic and fast-paced. They identify the short product life cycle and fast technological progress as their major challenge in competition. They are worried if they fail to innovate or fail to get access to the most advantageous technologies, they may lose ground in this sector. They also perceive that "scale" has become a significant factor in competition of electronics components and that independent suppliers have a natural advantage in this aspect. Generally speaking, these electronics firms are under fierce competition in technological innovation and cost reduction simultaneously. This pressure has shaped the individual companies' boundary strategies. In terms of the future, they feel it is hard to predict the competitive landscape of the sector because it is still very dynamic, but they think that perhaps the products may become more and more modular and standardized.

In 1991, the division was restructued into GM's Automotive Components Group, which in 1995 was renamed to Delphi Automotive Systems.

[25] During the interviews, as in many documents on automotive supply chains, the managers often talked about "tier-1 supplier", "tier-2 supplier", etc. In some cases, they are sure about which supplier is on which tier. However, in some other cases, they also admitted that the suppliers can be found on both tier 1 and 2 (or even 3)

- **Strategic Responses: Active Industrial Transactions and Architectural Innovations**

First, the companies feel pressure and need for active procurement. A firm strives to procure rather than make in-house when better technologies, necessary production capabilities, or lower costs that are crucial for retaining the competitiveness of its specific set of system products are only available outside the company. Historically, the internal component divisions of integrated companies satisfied internal needs, but they have been more and more disadvantaged in competition with independent suppliers on production scale and efficiency of product development. External procurement sources often include independent suppliers, affiliated keiretsu suppliers, and the component divisions of (partially) integrated diversified electronics manufacturers (even competitors).

Electronics firms procure mostly standardized components (e.g., semiconductors, LCDs, batteries), and they expect more standardized components and parts in their future procurement portfolios. Some firms told me that they have initiatives to standardize the components needed by multiple internal divisions, so that the corporate procurement team may coordinate to procure items in high volume in order to gain the bargaining power with suppliers and lower purchasing prices.

Second, short product life cycles push companies to sell some of their intermediate components to the industrial markets when demand exists, because the technology advantage of an electronics component often lasts only a short while. When a company achieves a

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because they may supply to both assemblers and other suppliers, which supply to assemblers.

technology advantage with a component, it is usually willing to sell to the industrial market to maximize the revenue from that temporarily held technology advantage. Once the advantage depreciates, the focus of competition shifts from product innovation to cost. Even then, the company still strives to sell to the industrial markets in order to improve its economy of scale and lower unit cost. An integrated firm that I interviewed has an Industrial Marketing Group at corporate headquarters that promotes component products. Generally, the participation of integrated firms in the industrial component markets may help their internal divisions benchmark their operational efficiency and effectiveness with industrial frontiers and remain competitive with the more specialized independent suppliers.

Third, electronics firms are driven to innovate and conduct intensive product development. They all perceive that there is enough potential to mix and match knowledge and technologies at the component level to create new integrations of products at the system level. This motivation offers a partial explanation of why most electronics firms are diversified on their horizontal boundaries.

- **Vertical Firm Boundary: Permeability**

On one hand, previously integrated electronics firms are pushed to procure components from external suppliers that can offer better performance, price, and quality than internal divisions. On the other hand, the previously integrated firms also tend to disintegrate their component divisions, or spin off their component or device divisions to create independently run joint ventures. This means that independent suppliers will gain an increasing share of revenue over entire value chains. If this trend persists, the overall Japanese electronics sector may follow the path of the American personal computer sector, evolving from a vertically integrated sector to a fully modular one (Grove, 1997; Baldwin and Clark, 2000) in which companies mostly specialize in specific stages or areas of the value-adding process.

However, from the time that my archival data covers (the early 1990s) the Japanese electronics sector had not experienced vertical disintegration to the extent of its American counterpart. Figure 5.3 shows the trends in the ratios of component sales to total electronics products sales at major Japanese and American diversified electronics firms in the past two decades. It is striking that the previously-permeable American firms increasingly disintegrated and specialized in either components (e.g., TI) or systems (e.g., HP, Motorola), while the Japanese diversified electronics firms kept a comparatively constant ratio (about 15% to 25%) of sales of components produced in-house. Texas Instruments' percentage of component sales rose from about 50% to about 95% between 1991 and 2008. Motorola and HP are no longer suppliers of components to the industrial markets but have become pure system integrators. Meanwhile, many of the major industry players, such as Intel, Seagate, Microsoft, etc, were born specialized and remain constantly specialized on one vertical segment.

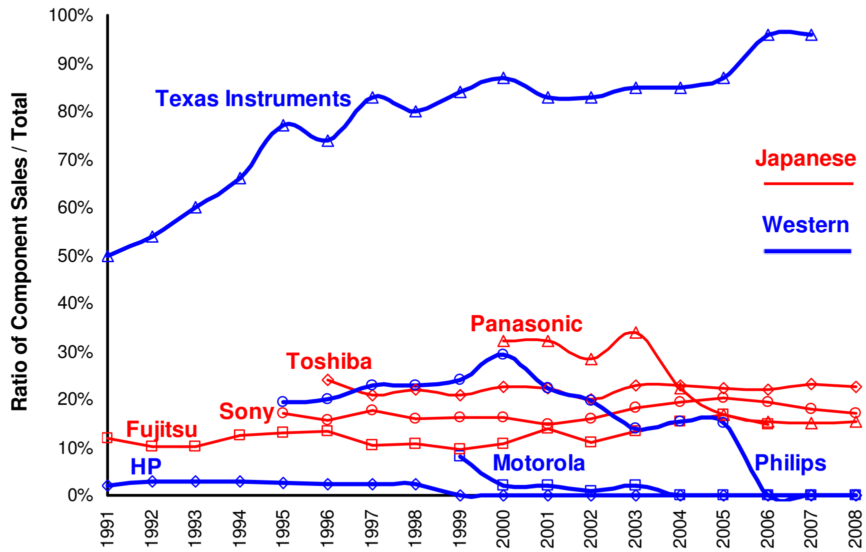

Figure 5.3 Ratio of component sales to total product sales of diversified electronics firms from Japan and the U.S. (and the Netherlands).

Note: The data are collected and compiled from the financial reports of these companies, which are publicly listed companies with their annual reports available online. The numbers for the Japanese firms and Philips from the Netherlands are compiled from segment data in their financial reports, while the numbers for the American firms come from the descriptive paragraphs of their annual reports.

Figure 5.3 indicates that the Japanese electronics corporations tend to pursue a permeable strategy on their vertical boundaries, while the major American electronics companies do not. Most of the Japanese interviewees envision that their companies will continue to operate internal component or device divisions for both internal transfers and external sales to industrial markets, while they also actively procure components from external suppliers[26].

I specifically asked interviewees about the motivation for such a strategy. Their main answer was that they still see the value of having the component business in house because of the

[26] At only one of the firms I interviewed, the director of procurement believes in that his company will be evolving into a pure system integrator by giving up component business totally.

potential that economical architectural innovations may emerge from mixing and matching know-how and capabilities at the component level. For example, the TV department of Sony developed a new slim TV that physically separates the screen (only 9.9 mm) and the main box while connected by wireless signals. The TV department adopted necessary wireless communication technologies from the Communication Network division and engaged engineers from that department in the development process. In another case, Samsung applied an LED backlight technology developed in an internal division to its new LED-backlit TV as a replacement for fluorescent light tubes. Although Samsung is not a Japanese company and not included in my network data, it shows many characteristics similar to those of the Japanese firms.

Japanese companies value in-house knowledge and capability, incremental learning, and continuous improvements at the component level that allow them to remain capable of architectural innovations at the system level. This decision rationale is intertwined with several important perceptions that Japanese managers share:

- They perceive that there is enough potential to mix and match knowledge and technologies at the component level to create new integrations of products at the system level[27].
- The sector's technological dynamics and the firms' competition on product differentiation drive them to innovate and conduct intensive product development.

[27] This may indicate that complete vertical disintegration is more likely to happen when dominant product architectures have emerged (e.g., as in personal computers). Then the potential for architectural innovation is limited, though modular innovation is still active. In such cases, changes in industry structure are mainly driven by companies' pursuit of modular technological advantages and cost reductions. However, Japanese electronics companies are taking a more comprehensive approach to respond to the industrial environment, partially because they are still pursuing architectural innovations and believe it is worth doing so.

- Having shareable diverse capabilities in house may allow a company to deliver adaptive new system products to fulfill dynamic demands.
- An internal component division is retained largely because it can still run economically (if not profitably). This may be attributed to participation in the competition of the industrial markets, which improves internal division's efficiency and effectiveness in their use of resources and capacity. Some companies have chosen to spin off their component divisions, probably because of poor performance.

Despite a dominant architecture for personal computers, for most communication and consumer electronics products Japanese firms are still able to deliver new architectures with new functions by mixing and matching existing technologies at the component level. If architectural innovation dynamics and the companies' pursuit of architectural innovations persist, a purely modular or hierarchical structure of segmented industries will not easily emerge. Instead, companies may stick to the more integrative boundary model -- simultaneously vertically permeable and horizontally diversified. The analysis in chapter 6 argues that the electronics sector may retain dynamic innovations for a prolonged period due to the nature of the technologies used in electronics products.

- **Downstream Horizontal Firm Boundary: Diversification**

As partially discussed above, most Japanese electronics firms related their diversification strategy on their downstream horizontal boundaries to their permeability strategy on their vertical boundaries. This manifests itself in designing and producing various kinds of electronics products (PCs, cameras, mobile devices, TVs, etc). Though this phenomenon is historically established, it also exists because firms think they can benefit from economies of scope at the system product level to fulfill the diverse needs of the electronics markets. In addition, Japanese firms still see potential for creating new system products by mixing and matching knowledge and technologies at the component level.

This diversification strategy is feasible partly because different areas of the electronics sector require some human and physical assets in common. Engineers with general electrical and electronics engineering knowledge can be easily moved and shared across computing, communication, and consumer electronics divisions when needed. The kind of diversification displayed by Japanese electronics firms is related diversification (versus conglomerate diversification) (Teece, 1982). One interviewee identified his firm's core competitiveness as the ability to leverage capabilities at the component level in order to innovate, produce, and manage a diverse line of products at the system level. Appropriately sharing and exchanging ideas, technologies, and resources across area boundaries may also nurture architectural innovation in system products, such as the Sony Slim TV with wireless communications and the Samsung LED-backlit LCD TV mentioned in the previous section.

Figure 5.4 demonstrates a simple example of what is happening on the electronics value chains: horizontal diversification and vertical permeability.

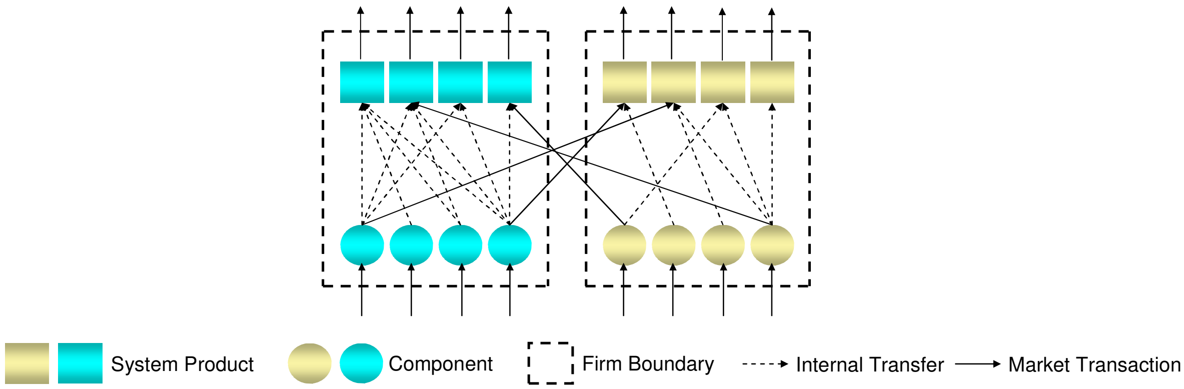

Figure 5.4 A schematic representation of the transactions on the horizontal and vertical boundaries of electronics manufacturers

- **Perceptions of Cycles and Messy Industry Architecture**

Interviewees observe a relatively high occurrence of supply cycles, which agrees with previous findings from the archival data in 1993. Interviewees also agree that the structure of transaction relationships among firms in their sector is messy and dynamic. Firms are often intertwined by cyclic transactions. They attribute the messy industry structure that they perceive to dynamic competition on technology and cost simultaneously.

- **Definition and Boundary of the Electronics Sector**

Due to the sharing of financial, technological, and human assets across divisions and companies, it might not be appropriate to analyze the value chains for computing, communications devices, and consumer electronics separately. In actuality, Japanese firms manage corporate-level decisions and operations for the production and sales of all kinds of electronics systems and components coherently and holistically. As one of our interviewees said, it is unfair to compare the performance of these Japanese companies with Nokia for cell phones, Dell for PCs, or Intel for semiconductors. The main competitiveness that Japanese firms aim to build is the ability to sustain and grow by leveraging component- and system-level capabilities across diverse but coherent electronics business areas. Therefore, the network of firms connected by electronics-related transactions constitutes a coherent industry sector–the electronics sector[28].

5.4 The Emergence of Transaction Cycles

Both the archival data and the interviews show the wide presence of transaction cycles in the electronics sector. Transaction cycles may not be a conscious design choice of the companies that form them, but rather be an emergent phenomenon from the collective behaviors (e.g., boundary structures) of individual firms following similar rationales in response to their industrial environment and technological dynamics. Three firm-level behavioral characteristics may have contributed to the high occurrence of supply cycles in the electronics sector: vertical boundary permeability, horizontal boundary diversification, and the autonomous distribution of competitive advantage. Among them, vertical boundary permeability is a necessary condition for the creation of a cycle. The other two facilitate the creation of cycles but are neither necessary nor sufficient for the creation of a cycle.

First, when companies open up their vertical boundaries to buy and sell in the industrial

[28] Some firms also have business areas distant from electronics, for example, real estate, financial services, etc. Despite encompassing all kinds of electronics products (e.g., TVs, mp3 players, computers, phones), our definition of the electronics sector in this dissertation excludes such non-electronics businesses of the firms that are included in our network analysis, such as Hitachi. Non-electronics transactions are not counted in the electronics sector analysis.

markets (i.e., make their vertical boundaries permeable), they may simultaneously act as a upstream supplier of smaller (or equivalent) components and an downstream integrator of larger (or equivalent) systems. In such a case, transaction cycles may emerge. Note that buying and selling activities on the permeable vertical boundary are different from the sequential buying of smaller components and then selling larger systems that integrate the bought smaller components, which is a flow across the upstream and downstream horizontal boundaries of a single firm. Figure 5.5 demonstrates this with a conceptual example in which nine firms work on the five-step production chains of a single product.

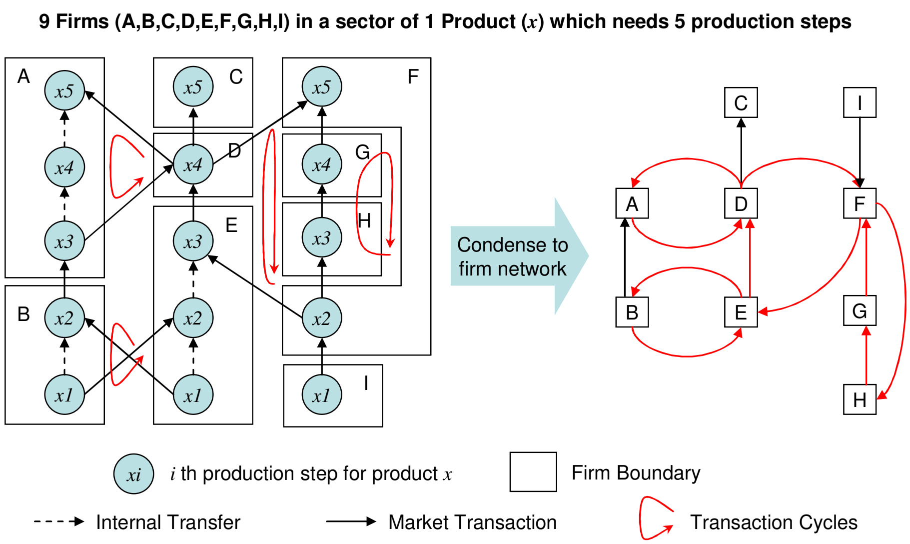

Figure 5.5 Vertical boundary permeability and the emergence of transaction cycles

In this case, there are nine firms on the five-step value-adding chains that produce product *x*. Four cycles are found: 1) A<->D; 2) B<->E; 3) D->F->E->D; 4) H->G->F->H. These example cycles clearly demonstrate that, because the value-adding chains are always unidirectional (i.e., sequential), in order for a cycle to emerge between two (or more) firms, *one of the firms must simultaneously buy components for internal integration and sell components (which are made at a lower stage than the integration stage for which it* *procures) for other firms' integration uses*, i.e., its vertical boundary must be permeable. It does not matter if all the other firms on the cycle are only specialized in one stage of the value chain, or not. That is, *for a supply cycle to be closed, at least one, though not necessarily all, of its members must be "permeable"*[29]. In brief, vertical boundary permeability is a necessary condition for cycle formation.

The interviewee at company D (the pseudonym from Table 5.1) provided a real contemporary example, similar to the A<->D cycle in Figure 5.5. Company D has a wholly owned subsidiary company called DD that designs and manufactures package substrates and printed circuit boards (PCBs) for chipset makers. For example, DD sells package substrates to another company X, a major chipset and device supplier based in Silicon Valley. Company X uses the substrates it buys from DD in the chipsets that it further assembles and sells to company D and other customers. This creates a supply transaction cycle. In particular, the interviewee emphasized that company D's procurement from company X and X's procurement from DD were spot-market transactions and independent of each other. Company D does not have central planning over this supply flow cycle. In the cycle, companies D and X contribute their specialized expertise at different steps of the value-added process, and the key to the formation of the cycle is that company D has competitive strengths in two roles: system integration, which needs company X, and package substrate, which X needs.

Second, the existence of many horizontally diversified firms may increase the probability that cycles will emerge, because downstream horizontal diversification means diversified

[29] Here we assume that all procurement transactions are only for further integration into larger products. If transactions for tooling and office uses, etc, are also included, this argument does not hold.

procurement needs as well as diversified potential competitive advantages that can sell. In both the empirical data analysis[30] and the interviews, we have found that most of the cycles involve diversified electronics corporations. The example in Figure 5.6 demonstrates how horizontal diversification may contribute to the occurrence of transaction cycles. To produce product *y,* firm C sources a component of *y* after step 2 from firm A and its own internal division simultaneously. Meanwhile, firm C sells the component of *x* after step 3 to firm A. This creates a transaction cycle between firm A and C. This differs from the case in Figure 5.5 in that the transactions here are on different production chains, for two products, *x* and *y*. In this case, if both firm A and firm C were not diversified, this cycle would not exist.

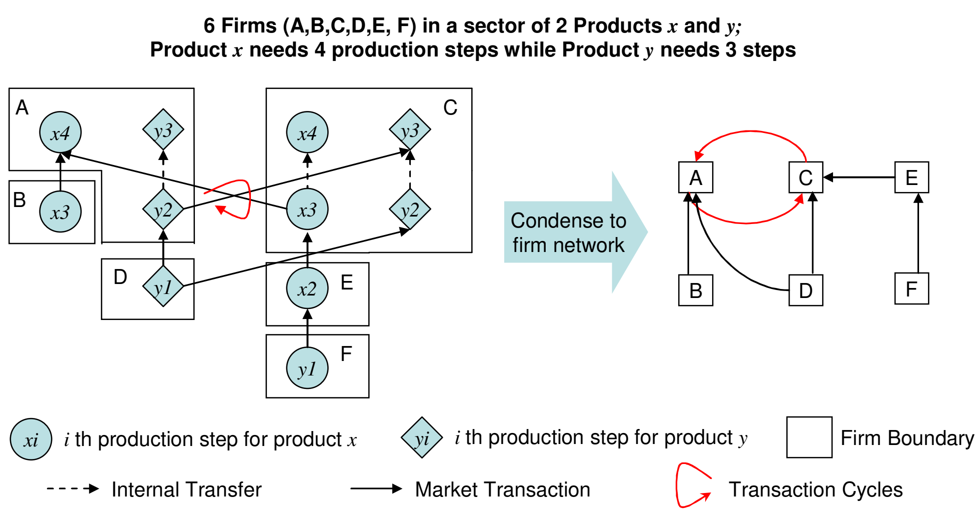

Figure 5.6 Downstream horizontal boundary diversification and the emergence of transaction cycles

However, downstream horizontal diversification is neither a necessary nor a sufficient condition for cycle creation. Figure 5.5 has shown that cycles may emerge on the production chains of a single product. Furthermore, Figure 5.7 shows that diversified firms (the same as the ones in Figure 5.6) may sequentially array on parallel production chains, without needing

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30 See the related result in sector 3.6.2

cycles to complete production.

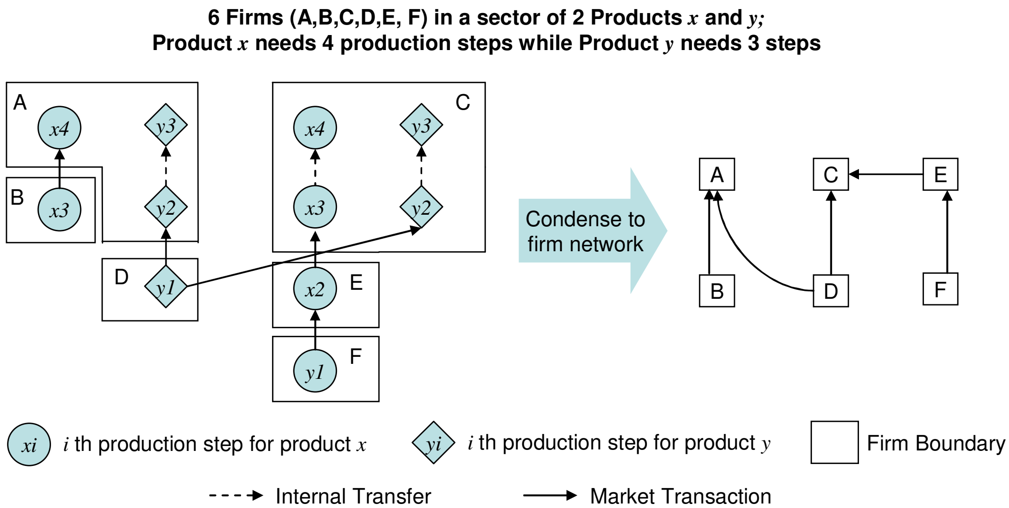

Figure 5.7 Horizontal boundary diversification and hierarchical production flows

Third, in the electronics sector, competitive advantages in technology, capabilities, or cost are autonomously achieved, dispersed widely, and temporarily held at different firms throughout the sector. In such a manner, the same group of firms tries to develop an overlapping set of technologies or capabilities, but no one knows who can achieve what at what time. Once one firm happens to achieve something valuable, the other firms may strive to procure from it. As there are many such “things,” the firms that can supply and the firms that need to procure are connected by “random” spot-market transactions. This effect increases the probability that cycles will form[31].

Therefore, a large number of transaction cycles emerge in the Japanese electronics industry sector, due to the number of major firms taking the permeable vertical boundary strategy and

[31] This is largely determined by the high modular innovation dynamics of the electronics sector, in which firms independently conduct innovation or improvement activities. One firm may achieve this technology or cost advantage while the other firm may achieve that, and they often need and want to transact to complement their separate achievements. This issue related to modular innovation dynamics will be further discussed in Chapter 6.

diversified horizontal boundary strategy[32], as well as the random distribution of competitive advantages throughout the sector. These conditions may be enabled by more fundamental forces that do not exist in the automotive sector, where we do not observe the two boundary strategies and the random distribution of competitive advantages.

However, in spite of being in the same electronics business, as indicated in Figure 5.3, the American electronics companies tend to be specialized on single value-adding stages, so the vertical boundary permeability condition (which is the necessary condition for cycle emergence) may not popularly exist in the current American electronics sector. Therefore, the American electronics sector might be relatively more hierarchical than the Japanese electronics sector. More research is needed to prove or reject this conjecture.

5.5 Summary: Sector Differences

Table 5.2 outlines the responses commonly provided by the interviewees in each of the two sectors. This summary by sector sheds light on some differences between the sectors in terms of firm boundary strategies, transaction structures, industrial environments, and related managerial rationales.

Table 5.2 Categorized interview results

	Automotive Sector	**Electronics Sector**
Horizontal Boundary	Specialized	Diversified (Coherent)

[32] To repeat one result already given in Chapter 3, I find only 7 two-node cycles left after removing the largest 10 electronics firms (by revenue) from the network. In the new network without the top 10 firms, 14 out of 221 links are on cycles, i.e. h=0.9367.

Vertical Boundary	(Concurrent) Sourcing	Permeable
Are Tiers Perceived?	Yes	No
Are Cycles Perceived?	No	Yes
Industry Status	Saturated; Slow-paced	Highly dynamic; Fast-paced
Attitude on Innovation	Strategically insignificant	Significant
Major Challenges/Risks	1) Excess competition on price & quality 2) The loss of incentive and capacity to innovate 3) Over-reliance on the pull of customers Example from both firm B and C: customers cannot pay in time; small suppliers face bankruptcy in economic recession.	1) Short product life cycle; Dynamic technological progress 2) Intensifying competition on "scale" of electronics manufacturing
Keys to competition	QCD: Quality, Cost, Delivery	Innovation/new products; Cost/Economy of scale
Key strategies that may affect the scopes of customers and suppliers	Deepen trust and relationships with current customers by increasing specificity of products and processes to improve QCD	1a) Buy components from anyone for advanced technology or low cost 1b) Standardize components across division for volume procurements 2) Sell temporarily advantageous components anywhere for scale up 3) Develop new system products via architecture innovations (mix and match)
Future trends	Same products (to same customers or same kind of customers) with improving quality; Depending on the needs of automotive customers.	Uncertain; Perhaps the products become more and more modular.

Firms in the automotive and electronics sectors have chosen very different horizontal and vertical boundary strategies (i.e., transaction patterns). On the vertical boundaries, the internal component divisions of electronics firms tend to sell to the intermediate industrial markets. Such transactions are not observed in the automotive sector. On the downstream horizontal boundaries, automotive manufacturers are specialized in automobiles, and automotive suppliers are dedicated to automotive-related products. Electronics firms normally operate a diverse line of system products that span computing, communication, and consumer electronics.

The managerial perspectives on the industrial environments and decisions rationales indicate that the differences in boundary structures and strategic transaction choices between the sectors may result from the differences in innovation dynamics between the two sectors. Short product life cycles and costs are perceived as the major challenges in the electronics sector, driving firms to actively procure and sell components in the industrial markets via their vertical boundaries, in order to remain competitive on both the horizontal and vertical boundaries. In contrast, cost and quality, rather than technological change, are identified as the keys to competition in the automotive sector. This pushes firms to pursue specificity in products, processes, and transactional relationships in order to improve the quality of system integration, rather than developing new products and new customers. Automotive managers perceive limited potential to develop new products because of the well-honed dominant automotive design.

In brief, in a dynamic industry setting, electronics firms favor standardization and open transactional relationships. In contrast, in a mature industry setting, automotive suppliers pursue specificity in products, processes, and customer bases. In the Japanese electronics sector, transactions cycles widely emerge, as the major firms take the permeable vertical boundary strategy and actively conduct industrial transactions to buy or sell technology or cost advantages that are autonomously achieved, dispersedly distributed, and temporarily held by firms across the sector. In the automotive sector, suppliers are compliant with their positions in the tiers of the production value chains. Interviewees from the automotive sector widely accepted the tier architecture, which does not make sense from the perspectives of the interviewees in the electronics sector. In general, the observed difference in inter-firm transaction patterns of the two sector agrees with our finding in Chapter 4 –that the transaction specificity of the Japanese electronics sector is much lower than that of the automotive sector, and agrees with our finding in Chapter 3 –that due to the wide presence of the supply cycles, the electronics sector exhibits a much lower degree of hierarchy than the automotive sector in Japan.

The interviews also shed light on some links between horizontal and vertical firm boundary strategies. For example, the diversified downstream horizontal boundaries and permeable vertical boundaries in the electronics sector are the simultaneous results of dynamic market needs (short product cycles) and managerial motivations to pursue architectural innovation by mixing and matching component-level technologies across internal divisions. This may indicate that, if a firm chooses to pursue only one of the two strategies, the other may fail to hold. As we have discussed, American electronics firms choose neither of the two strategies, but rather horizontal specification and vertical disintegration.

There may be underlying fundamental forces that allow these strategic transaction choices (i.e., horizontal diversification with vertical permeability) in the electronics sector but constrain them in the automotive sector. I will explore these underlying forces in Chapter 6.

5.6 Chapter Summary

This chapter summarizes the interview results and finds some significant differences in industrial environments, transaction strategies and underlying decision rationales of firms between the two sectors. These findings are composed into the conceptual framework and diagrammatic representation of two kinds of firm boundaries, where transactions take place. These differences in firm boundary strategies have led to the differences in transaction specificity and the degree of hierarchy in industry architecture of the two sectors in Japan. However, the differences in industrial environments, transaction strategies, and decision rationales may in turn result from more fundamental economic and technical forces which Chapter 6 will explore.

Chapter 6

The Power of Power: How Technology Constrains Strategy and Influences Industry Architecture

"It is the theory that decides what can be observed."

-- Albert Einstein

In this chapter, by synthesizing the findings from empirical network data analysis, modeling and simulation, interview results, and existing knowledge on product technologies, I further trace the difference in transaction patterns and firm strategies of the two sectors to their difference in the fundamental properties of the underlying technologies.

6.1 The Technological Regime of Industry Sector

The data analysis shows that the automotive sector has a higher degree of hierarchy, indicating higher transaction specificity, than the electronics sector. The interview results also demonstrate higher transaction specificity in the automotive sector, indicating a greater degree of hierarchy in the automotive sector than in the electronics sector. In particular, the analysis in Chapter 5 has indicated that individual firms' transaction-related strategies and behaviors are strongly tied to technological dynamics in the two sectors, as perceived by the mangers that design the strategies. This indicates that the differences in industry architectures and inter-firm transaction patterns may in turn result from the differences in the fundamental technological regimes (Nelson and Winter, 1982; Malerba and Orsenigo, 1993; 1996; 1997; Malerba, 2002) of the two sectors. While our two subject sectors are similar in many business and economic aspects, they differ substantially in terms of the technologies that underlie the products innovated, developed and produced in the respective sectors.

Technology is a set of techniques, tools, or processes which turn knowledge, ideas or principles into practical value for certain functional purposes. The term "technological regime" is the technological environment, in which firms' innovation, learning, and production activities take place. Sectors differ greatly in terms of their technological regimes (Nelson and Winter, 1982; Dosi, 1988; Malerba and Orsenigo, 1996; Malerba, 2002; Castellacci, 2007), when the technologies that underlie different sectors are different.

The technological regime literature has shed light on how the characteristics of technological regimes shape incentives and constraints, and affect the basic behaviors and performance of economic agents in different sectors (Malerba and Orsenigo, 1993; 1996; 1997; Castellac, 2007). In principle, the characteristics of technological regimes may also influence the transaction-related strategies and behaviors of individual firms, which in aggregate determine sector architectures. Prior studies have suggested how product and process designs may affect the firm's transactional boundaries or make-or-buy decisions (Fine and Whitney, 1996; Fine, 1998; MacDuffie, 2006; Baldwin, 2008). Here, I link these insights to the fundamental technologies underlying product designs, innovation dynamics, transaction specificity, and the hierarchical aspect of industry architecture, in an industry sector.

Technologies that underlie the designs of specific products can be classified by their basic functions (Hubka and Eder, 1988; vanWyk, 1988; Magee and de Weck, 2004), in terms of operands (matter, energy, and information) being changed by operations (storage, transformation, and transport) (Koh and Magee, 2006). Our two comparative sectors are substantially different in terms of the constraints imposed on them by the basic ways in which their products fulfill their respective functions. Electronics products mainly handle information: storing, transforming, and transporting it. By contrast, automobiles act on matter (storing fuel and transporting humans and goods) and on energy (transforming physical-chemical energy to kinetic energy and transporting energy from the engine to the wheels).

In the following, I will explore the impacts of the fundamental technologies used in automobiles and electronics on firm transaction patterns and industry architectures of the two sectors, which have been observed, measured and modeled in the forgoing chapters.

6.2 Automotive Sector: A Socio-Technical Analysis

- **The High-Power Nature of Energy Processing in Automobiles**

In an automobile, significant energy is processed, and significant power is involved in the functioning and interactions of its components. Although there is a trend to replace mechanical signal processors with analog or digital electronics (Whitney, 1996), there are physical limits on such substitutions, given that an automobile's main purpose is physical motion. High power is the basis for the automobile's behavior and the main expression of its basic functions.

- **High Power Leads to Product Specificity**

The functional parts of an automobile are tightly connected by the basic premise of high power. High power creates difficult-to-anticipate side effects, such as heat and vibration (Whitney, 1996). There are also a number of systemic requirements, including energy efficiency, emissions, noise, vibration, safety, stability, driving feel, design, cost, etc, which need to be met in order to attract consumers. These require intensive interactions across different functional and physical sub-systems (MacDuffie, 2006; Fujimoto, 2007).

As a consequence, there is a high level of interdependency in the design and use of the components. These interdependencies manifest themselves as carefully specified performance requirements that require a tailored response by a supplier who designs the component and its interfaces to other items. Components cannot be designed independently from, or without detailed knowledge of, the products in which they will be used (Whitney, 1996). Therefore, the major automotive components and their mutual interfaces are basically product-specific

(MacDuffie, 2006). Piston rings, seats, and mufflers, while obeying well known physical laws and performing well understood functions, nevertheless are generally designed and tested again each time a new vehicle is designed.

- **Product Specificity Leads to Transaction Specificity**

In order to guarantee the quality of component matching, coupling and integration, product designs must be specifically tailored, and contracts between firms are "hand-in-glove." This component specificity, which Schilling (2000) called "synergistic specificity," may give rise to asset specificity (Williamson, 1975; 1981) between buyers and suppliers. Both buyers and sellers must invest in assets (including knowledge) that are valuable only in the context of their specific relationship (Baker, Gibbons and Murphy, 2002; Baldwin, 2008). Such asset specificity in turn gives rise to what we are calling "transaction specificity." In the language of our model, each upstream firm has a well defined "niche range" of customers that are "close" to each other in terms of what they make and what they need to know in order to deal with each other efficiently and effectively.

Interviews with three major suppliers on the automotive value chain, including one material supplier and two component suppliers, confirmed this pattern of a well defined set of similar customers. In general, the automotive suppliers claimed that they had to tailor their product designs and production processes to their specific customers' requirements, and meanwhile invest in deep, ongoing relationships with a stable group of customers. The Japanese customer and supplier firms engaged in such pragmatic collaborations have continuously improved their products and processes jointly (Sako, 1992; Helper, MacDuffie and Sabel, 2000)[33]. Such relationships generally take a long time to build and may give rise to organizational rigidities (Kaplan and Henderson, 2005). We also found that the interviewed firms' are either unwilling to diversify their product portfolios, or incapable of creating new products for customers outside their main niches (see examples given in Chapter 5). These supplier firms are captive to their automotive suppliers (Christensen, 1997).

Finally, as our model shows, when this pattern of high transaction specificity is aggregated to the sector as a whole, it gives rise to hierarchy – that is, unidirectional transactions from companies to companies in the sector.

6.3 Electronics Sector: A Socio-Technical Analysis

- **The Low-Power Nature of Information Processing in Electronics**

In electronics products (e.g., computers, communications, and other consumer electronics), information or signals are processed and transferred in binary logic or low-power analog signals. Such processes are relatively economical, accurate and reliable, and can be accomplished at very low power levels. Such products have limited size and weight. The interactions among different functional parts of an electronics product are relatively weak (Whitney, 1996). Lower power entails less severe and less frequent difficult-to-anticipate side

[33] Fujimoto (2007) argued that the capacity to collaborate and a favorable attitude toward collaboration have granted the Japanese firms architecture-based comparative advantages in producing and exporting integral products, of which the automobile is a typical example. However, this Japanese advantage in collaboration for tight product coupling is not obvious in producing relatively modular products.

effects, so the integration of parts is relatively easy. Such cases are often regarded as "modular" (Baldwin and Clark, 2000). There are degrees of connection in electronics products, implying graduations of modularity.

- **Low Power Allows Product Modularity**

At one extreme of modularity, codified behaviors and standardized interfaces are pursued economically and reliably. Standardized interfaces guarantee that the behavior of components does not change when they are combined, as long as some design rules are obeyed. In contrast to automobiles, the design and production of many electronic components, such as memory chips and batteries, can be conducted without detailed knowledge of the products in which they are to be used (Whitney, 1996). Even though some electronics components are customized to some extent in some situations, such as novel product development (Yasumoto and Shiu, 2008), the low power transfer in the connections between electronics components still allows them to be more "modular" than the energy-processing mechanical components of automobiles, such as the engine and transmission[34]. Thus, extra coordination and customization efforts in electronics may not increase asset specificity to the level required in integrating automotive components.

- **The Power of Modularity (1): Low Transaction Costs and Low Asset Specificity**

[34] Fujimoto (2007) surveyed product development personnel in various assembly industries for their subjective evaluations of architectural attributes with regard to the integrality versus modularity of 177 assembled products. The responses on different architectural attributes were aggregated into a single "integralness" index. The results indicate that, from the managers' perspective, passenger cars are far more integral than most electronics and

The modular, low-power nature of electronics has several further implications for transaction patterns. First, modular interfaces are the thin crossing points (Puranam and Jacobides, 2006; Baldwin, 2008) where transaction costs (Coase, 1937) are low, resulting in low asset specificity between suppliers and customers (Williamson, 1975; 1981; Baldwin, 2008). This in turn makes arm's-length contracts and/or spot-market transactions economical: there is no need for the hand-in-glove relationships that are common in the automotive sector.

- **The Power of Modularity (2): The High Dynamics of Modular Innovations**

Second, the modularity of electronics allows independent, unsynchronized (versus interdependent and simultaneous) development activities, which in turn leads to high rates of modular product innovations (Baldwin and Clark, 2000) and short product cycles[35]. Koh and Magee (2008) showed that information technologies have exhibited much higher performance progress rates than energy technologies over the past 100 years. This also creates volatile demand -- what customers want this year is not the same as last year -- and thus increases firms' need to develop and maintain customers in more than one well defined market niche.

The modularity of electronics components favors more specialized independent suppliers, which have larger production scales and faster product development than the less efficient internal component divisions of large, vertically integrated electronics firms, particularly for such standardized components as semiconductors. Thus, as our interviews with major

electrical products.

[35] Three major electronics manufactures that we interviewed identify "short product life cycle" as their major challenge. The interviews with automotive suppliers did not highlight this issue. Short product life cycles drive up competition on new technology and cost simultaneously, and many of the firms' make-or-buy strategies are

electronics companies in Japan indicate, the previously integrated electronics firms are pressured to actively procure components from external suppliers that can offer better performance, price, and quality than internal production[36]. Meanwhile, the internal component divisions of big electronics companies also strive to sell components to the industrial market (at the same time serving internal needs) in order to use resources and capacities more effectively, link complementary capabilities, and benchmark to improve efficiency to industry standards. This hybrid "sell-and-buy" approach represents the permeable vertical boundary strategy (Jacobides and Billinger, 2006)[37] discussed in Chapter 5. When a company fulfills multiple roles, i.e. having multiple vertical value-adding steps in house, and simultaneously buys components from and sells components to the industrial market via its vertical boundary, transaction specificity can be reduced to the extent that cycles will likely emerge around this company[38].

- **The Power of Modularity (3): The High Dynamics of Architectural Innovations**

Third, the modular (if not standardized) electronics components can be mixed and matched with each other to generate a variety of distinct system products economically (Whitney, 1996). On one hand, this indicates the coherence (in the component-level knowledge) of the diversified system products of the major Japanese electronics firms (Teece, Rumelt, Dosi and

responses to it.

[36] Paprzycki (2005) also observed the increasing outsourcing of electronic and optical components from independent suppliers, affiliate suppliers, and even the component divisions of competitors, since the 1990s in the Japanese electronics sector.

[37] Past research on firm boundaries (empirical studies in particular) have largely focused either on make-or-buy as a dichotomous choice, or concurrent sourcing, i.e., both make and buy (Parmigiani, 2007), neglecting the "provide" and "sell" transactions which may happen concurrently.

[38] Theoretically, if all transactions are only for further integration into larger products (excluding tooling, office uses, etc.), any supply cycle must include at least one member with permeable vertical boundary. (See Chapter

Sidney, 1994). On the other hand, it means that a firm making particular components can have a wide range of customers making very different products, indicating low asset specificity. For example, a flash memory chip supplier may have customers that produce cell phones, cameras, or the components of larger system products. As a result, the customers of an electronics supplier are not constrained to a well defined niche, but may be located almost anywhere in the industry. Our simulation models show that, when aggregated, this low level of transaction specificity gives rise to a correspondingly low degree of hierarchy in the overall sector.

In addition, the ease of mix-and-match sustains the dynamics of architectural innovations (Henderson and Clark, 1990) and the motivation of the diversified electronics companies to pursue architectural innovations. Historically, the Japanese electronics industry grew upon its success in adapting existing fundamental electronic and electrical technologies to develop successful system applications, such as radios, walkmans, etc. (Nakayama, et al, 1999). A manager I interviewed said that such a motivation partially explains why Japanese firms prefer the integrative organization choice of permeable vertical boundary (for intermediate industrial products) and diversified downstream horizontal boundary (for system products) versus complete vertical disintegration (e.g., HP) and downstream horizontal specialization (e.g., Nokia) -- the diverse component-level technologies, capabilities, and resources of different divisions may be potentially remixed and recombined across divisional boundaries to create new system products when this is found to be valuable[39].

5.4 for details on the conditions that allow and encourage cycles likely to emerge.)

[39] This is a partial motivation. First, firms diversify partially in order to tackle dynamic and compound demands. Second, another firm that we interviewed prefers vertically permeable boundaries to complete disintegration because the component divisions remain profitable by benchmarking with peers through the permeable

- **Modularity Leads to Low Transaction Specificity and the Emergence of Cycles**

In general, the modularity of electronics components and parts may drive autonomous and rapid innovation, meanwhile keeping transaction costs and asset specificity low. Driven by the short product life cycle (due to high innovation dynamics) and facilitated by low transaction costs and low asset specificity, firms tend to be permeable on the vertical boundary, be diversified on the downstream horizontal boundary, and actively conduct spot-market transactions, in order to survive and sustain. With such conditions, transaction specificity may decrease to the degree that cycles begin to emerge autonomously throughout the electronics sector.

6.4 The Theory: Linking Technology, Strategy, and Industry Architecture

In summary, the foregoing analysis has shed light on how industry architectures might be in part influenced by the technological nature of products through a chain of logic, which correlates the nature of technologies (energy versus information; high power versus low power) to product architectures (integral versus modular), innovation dynamics (slow versus rapid), transaction-related firm behaviors, transaction patterns (specific versus open) and industry architecture (hierarchical versus cyclic).

On one hand, the high-power nature of an automobile promotes mutual specificity in its

boundary.

components, production assets, and transactional relationships, requires hand-in-glove contracts, and limits innovation dynamics. High levels of transaction specificity across a sector give rise to hierarchical industry architecture. The flow chart in Figure 6.1 describes the entire chain of influences, from the high-power nature of automotive energy processing to the high degree of hierarchy in the architecture of the automotive sector.

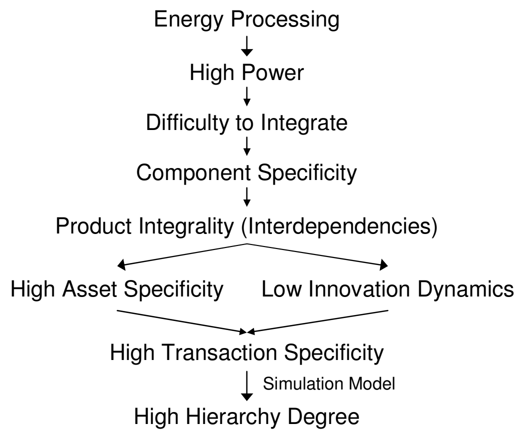

Figure 6.1 Causal relationships underlying the industry architecture of the automotive sector

On the other hand, the low power of electronic components enables modular product architectures, leading to low asset specificity between suppliers and customers, low transaction costs and spot-market transactions, high rates of innovation, and intense competition on technology, scale, and cost. In such an environment, the Japanese firms choose not only to diversify their end-user product lines, but also to make their vertical boundaries permeable and play multiple roles on the value chains. All of these factors lead to low levels of transaction specificity across a sector, which further give rise to non-hierarchical and multidirectional industry architecture. Figure 6.2 describes the entire chain of influences, from the low-power nature of information processing in electronics to the low degree of hierarchy in the architecture of the electronics sector. Particularly, note that the combination of horizontal diversification and vertical permeability are strategic choices feasible in electronics business which are generally taken by Japanese firms, but they are not seen being favored by the major American/Western electronics firms[40].

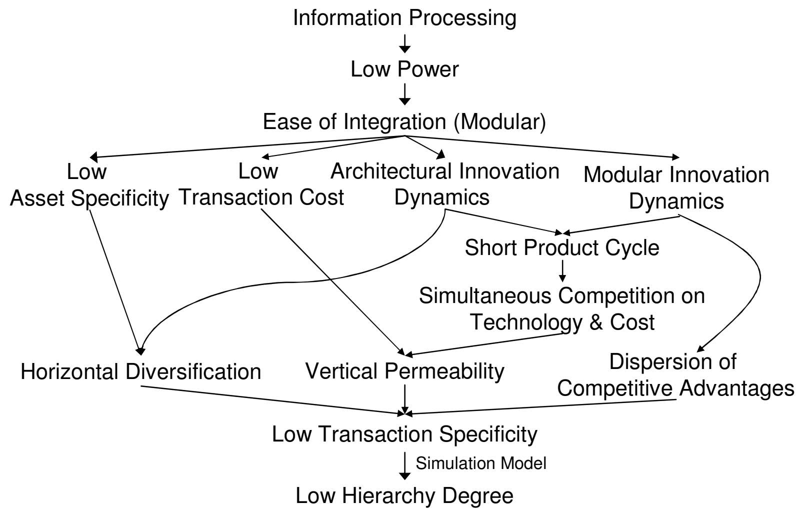

Figure 6.2 Causal relationships underlying the industry architecture of the electronics sector

Thus, high and low levels of transaction specificity are logically traced back to differences in the power levels of the underlying product technologies. In our causal model in chapter 4, high and low levels of transaction specificity lead to high and low levels of hierarchy in the resulting networks of transaction flows. Thus the concept of transaction specificity serves as a bridge between an observable macro property of the sector's architecture—hierarchy— and its technological regime—the requirements that technology places on individual transactions between firms.

Based on the analysis above, I argue:

The higher the power level of a sector's technologies, the higher the degree of transaction specificity, and the more hierarchical the sector's transaction flows.

[40] The exploration for reasons for this difference of strategies between the Japanese and Western electronics firms is not within the boundary of this thesis. It is an interesting question for future research.

This argument is drawn from our exploratory analysis and comparison of two Japanese sectors that differ in their technological regimes but exist and evolve in a similar historical, cultural, and macroeconomic context[41]. It describes one type of physical constraint imposed on the strategic transaction choices of individual firms, and allows industry architecture to be partially predictable.

This argument, in another word, also says that high power level of a sector's technology is a sufficient condition for high transaction specificity at the firm level and high degree of hierarchy in industry architecture at the sector level. However, it is not a necessary condition for these economic interaction patterns, because the boundary strategies of the American electronics firms, which pursue specialization on both vertical value chains and horizontal markets, may also result in high transaction specificity and high degree of hierarchy in industry architecture, in a low power setting.

Although low power level of technologies is a necessary condition for the diversification strategy on the downstream horizontal boundary and the permeability strategy on the vertical boundary of the Japanese electronics firms, which resulted in low transaction specificity and low degree of hierarchy, the inversion of this argument may not hold, i.e. the lower power level of technologies does not suffice to lead to low transaction specificity and low hierarchy degree. Low power also allows firms to pursue other strategies, such as the American-style boundary choices, which do not result in low transaction specificity and low degree of hierarchy in industry architecture.

[41] I hope readers will view this conjecture as a call for awareness on the widely ignored influences of technology on industry architecture, rather than a claim that technology is the only factor that influences it.

In a nutshell, the insight from the analysis so far is that the strategic transaction choices of single firms may shape industry architectures, and meanwhile are constrained by the nature of technologies. More specifically, high power technologies constrain strategic transaction choices feasible for firms. Lower power technologies open up many possibilities for different transactional strategies. In another word, lower power technologies enable a larger option space for strategies, for companies to explore and exploit. In the low power electronics setting, we have observed different strategic transaction choices, vertical permeability plus horizontal diversification, vs. vertical and horizontal specialization. Meanwhile, these different strategies are not observed in the automotive sector.

6.5 Chapter Summary

In this chapter, I conduct social-technical analyses to link the results from previous chapters to Daniel Whitney's prior work on the physical limits to product modularity. I synthesize and propose a theoretical explanation of how the strategic transaction choices of single firms may shape industry architecture and are shaped by technologies. Thus, the difference in industry architecture of the two sectors may be traced back to the differences in the fundamental properties of the underlying technologies in the two sectors, via the firms' strategic transaction choices under technological constraints.

Chapter 7

Conclusions

This dissertation explores how firms are organized at the sector level, in order to understand how the strategic transaction choices by single firms may shape industry architectures, and meanwhile are constrained by technologies.

I take an industry sector as the unit of analysis, and use network analysis to measure the degree of hierarchy (one-way flow of transactions) in the architectures of the automotive and electronic industry sectors in Japan. I further create a network simulation model to relate sector-level hierarchy degrees to firm-level behavioral patterns. Finally, by linking the empirical measurement and analytical modeling results, my interview data, and existing technical knowledge of the products, I propose a theoretical explanation of how the technological base of a sector may influence transaction strategies and boundary designs of single firms, which in aggregate determine overall industry hierarchy.

7.1 Academic Contributions

This dissertation is built on the core concepts and theories of the institutional economics tradition of industry studies, including sector, industry architecture, hierarchy, modularity, transaction costs, and the boundaries of firms. This dissertation also uses techniques (e.g., social network analysis) and concepts (e.g. hierarchy, market niche, roles and positions) from economic sociology. It is expected to make several contributions to the established work in these fields.

7.1.1 Flow Hierarchy Metric

This dissertation develops for the first time quantitative evidence of the variable degree of hierarchy in industrial sectors. Previous theory has assumed pure hierarchical transaction relationships among firms in industry sectors or production markets, while assuming pure random or spot-market transactions among actors in the financial sectors. In some intermediate cases, real-world industry sectors (e.g., the electronics sector) are neither purely hierarchical nor purely random, but in the middle ground. Empirical evidence on hierarchy in large sectors is lacking.

I first identified and defined the type of hierarchy relevant to industry studies, i.e., flow hierarchy, then developed a network-based metric and algorithm to measure the degree of flow hierarchy in transactional relationships among firms. I applied this metric and algorithm to transaction data from two industrial sectors in Japan. The empirical results show that the electronics sector exhibits a significantly lower degree of hierarchy than the automotive sector, due to the presence of many transaction cycles.

7.1.2 Simulation Model of an Industrial Network

To explain the findings from the empirical measurements, I created a network simulation model to relate the degree of hierarchy of a sector to two firm-level variables: transaction breadth (i.e., how many transactional relationships exist) and transaction specificity (i.e., where the transactional relationships are relatively oriented). The model builds upon three rules about market structures: hierarchy, market niche, and the mapping relationships between the roles and positions of actors. I call this model "*adaptive niche model*" because it allows the adaptive transaction activities that deviate from the basic rules. It is the first model with random tunable networks that may represent industrial networks. Data from interviews with nine firms in the two sectors demonstrate the same results as the model and simulation analyses indicate.

7.1.3 Transaction Specificity

The concept of transaction specificity provides a bridge between the macro-level industry architecture and micro-level economic and technical factors that affect inter-firm transactions. The quantification of transaction specificity at the firm level is able to be achieved because we expand the level of analysis to the entire sector network. With the empirically measurable hierarchy degree and transaction breadth, using the simulation model, we are able to quantitatively infer that the transaction specificity in the electronics sector is much lower than that in the automotive sector. The interview data demonstrate the same result.

Interestingly, the creation of the transaction specificity concept has implications to multiple academic fields. From an institutional economics perspective, transaction specificity measures where transactional relationships are oriented, rather than whether a transaction is needed against in-house production, as prior studies have investigated. Thus, transaction cost analysis is extended from the boundary of firms to the transaction network of firms. From a sociology perspective, it quantifies the tendency of a firm to fix its roles according to its relative network position[42]. For engineering systems research, it bridges the gap of analysis between (inter-)organizations and product characteristics.

7.1.4 The Conjecture: How Technology Influences Strategy and Industry Architecture

Linking the results from 7.1.1, 7.1.2, and 7.1.3 to Whitney (1996)'s prior work on the physical limits to modularity, I argue that higher power level of a sector's technologies will lead to higher degree of transaction specificity and more hierarchical transaction flows across the sector. However, the inversion of this argument does not have to hold. Our limited evidence has shown that low power of electronics components allows the electronics firms to pursue some transaction choices that are not feasible in the automotive sector, i.e., permeability of vertical boundary and diversification of downstream horizontal boundary of the Japanese electronics firms, as well as vertical and horizontal specialization of the Western electronics firms.

[42] Our analysis has shown that the nature of technology underlying the transacted products influences such a tendency. This may point to a new direction of sociology studies – "technological sociology", a perspective that is different but related to "economic sociology".

This theory attempts to logically link the physics of technologies to the economics of inter-firm transaction patterns and industry architecture. Purely social science studies of industries have ignored the power of technology on social or economic organizing. So they could not explain why actors in one sector more tend to fix their roles than in other sectors. Here, by taking a socio-technical perspective, we are able to explore and synthesize the linkages between the physical and the social worlds, which de facto interact.

7.1.5 Implications

For academics, I hope this research will point the way to new approaches to understanding industry architecture and the factors that influence the architecture of an industry sector, and to understand the transaction-related strategies of single firms. The application of network analysis permits institutional economics to be extended from the structure of an industry to the architecture of a sector comprising multiple industries. Particularly, the application of network analysis at the sector level has allowed us to quantify, analyze and understand transaction specificity at the firm level.

In addition, the methodology developed in this dissertation, including the hierarchy metric, network simulation model, quantification of transaction specificity, etc, will allow more exploratory work in comparing the architectures of different industrial systems, observing the architectural evolution of a single industry sector, and comparing the evolving patterns of different sectors in terms of industry architecture.

7.2 Managerial Implications

For industry practitioners, this research suggests how strategic transaction choices of single firms may shape industry architecture, and also how such choices are constrained by the nature of technologies, as possibly summarized in Formula 7.1.

$$\textit{Inter-firm Transaction Pattern} = f\,(\textit{Strategy}\,(\textit{Technology},\ldots),\ldots) \qquad (7\text{-}1)$$

This research considers technology as a “variable”. More specifically, high power technologies limit strategic choices of industrial transactions feasible for firms, while lower power technologies open up many possibilities for different transactional strategies. In another word, lower power enables a larger options space for strategies, for companies to explore and exploit. This dissertation has also shown that companies in different countries have pursued different strategies in the same electronics context.

In general, I hope a deeper understanding of the relationship between the nature of technologies and industrial transaction strategies can guide a firm to tailor strategies to technical constraints imposed by the technical way the products deliver their functions, and to seek fully the strategic option space allowed by technologies in order not to ignore valuable strategic possibilities.

7.3 Limitations and Extensions

To advance the work in this dissertation further, a number of hurdles must be overcome. Primary among these is the difficulty of obtaining quality data. At present, I have data for only two sectors. The hypothesis suggested in this dissertation could be better tested if data for more, and more diverse, sectors are collected. It is usually difficult to collect and compile industry-wide data not only because of unclear industry boundaries but also the hesitance of some of the firms to share complete information on their transaction connections. This may lead to certain hidden sampling biases, and the empirical measurement bears the risk of the deficits in the data.

Second, as the ecosystem evolves its hierarchy degree may change (Simon, 1962; Luo and Magee, 2009). The products and processes of a sector evolve (Abernathy and Utterback, 1978). If two sectors are at different stages of their industry life cycles, this may contribute to some extent to the difference in their degrees of hierarchy. Our multi-year data show that the automotive sector has remained highly hierarchical over approximately two decades, but I do not have multi-year data to detect the evolving pattern of the electronics sector. I relied on the literature and our interviews (conducted in 2009) to show that cycles still exist, if not more widely, in the electronics sector, keeping its degree of hierarchy low. However, the electronics sector may become more hierarchical as it matures, and the degree of hierarchy in the automotive sector may decrease temporarily if a new technological paradigm (e.g., affordable electric vehicles) emerges and disrupts the current dominant design (Utterback, 1996). Thus I hope readers will view this dissertation's conjecture on the influence of technology on industry architectures as a call for awareness and future research, rather than a claim that technology is the only mechanism that affects corporate strategy and industry architecture. This also invites the further applications of the hierarchy metric and transaction specificity to examine the evolution patterns of industries and products where data exist, and/or identify the evolutionary stage (e.g. fluid, transitional or specific) of a specific industry or product at a specific time.

Third, automobiles and electronics operate under different technological constraints, summarized here in terms of the amount of power involved in their functions. This is an aggregate characterization that overlooks important facts. For example, some electronic products, such as laptop computers, use large amounts of power, a fact that constrains their performance in many noticeable ways. In addition, automobiles contain significant information processing capability and thus contain substantial amounts of electronics, a fact that joins the two industries in ways not represented here. This dissertation is limited in not indicating additional mechanisms that lead to asset and transaction specificity, beyond the high-power and low-power technologies considered here.

Fourth, we lack sufficient means for visually representing these large and complex networks. This is a known problem in network theory, and I have primarily followed the traditional method of dealing with it, namely to seek statistical metrics that are easy to calculate and have some explanatory power (Newman, 2003). The risk is that they summarize too much. There is great value in being able to "see" the network in order to tease out important architectural patterns that correlate with the aggregate quantitative metrics. I attempted to visualize industrial networks using network graphs and DSMs in Chapter 3, but the work on them is not sufficient. Further research toward these directions is needed.

At a more detailed level, the simulation model treats many variables, such as transaction specificity, as uniform within each firm and as the same for all firms in a given network. There are numerous ways to relieve this simplification, and using them will add nuance to the model by differentiating suppliers that play different roles at the system, subsystem, or discrete component levels of the network.

In addition, I mainly attribute the difference of transaction patters of firms in the Japanese automotive and electronics sectors to the difference in the nature of technologies of the two sectors. However, this dissertation has not explored and not tried to explain why the American and Japanese electronics firms have taken very different boundary strategies in the same technological context. Such differences may result from the differences of culture, historical, political interference, financial resources, or more complex eco-system co-evolution dynamics, etc, and need to be systematically examined. To me this is an interesting question, and I invite other researchers to explore possible answers to it.

These limitations may be seen as an invitation to explore these connections further in order to gain more and deeper understanding of the constraints and strategic possibilities of the industrial transactions by single firms, which in aggregate determine the architectures of industry sectors.

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Appendix A

Assessments of Alternative Hierarchy Metrics

Besides the hierarchy metric introduced in the main paper, I also explored other possible metrics that aim to quantify the degree to which the network architecture follows a flow hierarchy. The metrics are compared, and it is shown that the one proposed in the main text has advantages over the others in accuracy and ease of use.

A.1 Alternative Metric Base upon Cycle Identification

The first alternative hierarchy algorithm/metric to examine is to count the portion of nodes (instead of links) which are not included in any cycle over the total nodes. Proceeding in a way similar to the approach in the text of the main paper, I construct the node adjacency matrix first, and then raise the power of matrices to derive the node distance matrix. With the node distance matrix, we can check whether a node is involved in any cycle. One obvious disadvantage, compared to the one proposed in the paper is that, it neglects the layered hierarchy in its relative metric system. For example, in the example layered hierarchy network in Figure 3.3E, using this algorithm, all the 6 nodes are included in at least one cycle, so the hierarchy degree is zero. However, there is obviously an existing layered hierarchy. Instead, the hierarchy metric presented in the main text can identify the hierarchical link *d* in Figure

3.3E appropriately.

A.2 Alternative Metrics Based upon Level Identification

Both of the approach discussed above and the one introduced in the main text do not require ranking the nodes, but search for cyclic phenomena embedded in directed networks. Now, I examine the feasibility of other alternative ways to measure flow hierarchy, which are based on identifying the nonhierarchical links according to the pre-ranked levels of the hierarchy.

In the examples in the Figure 3.1 in the main text, the hierarchical types (regular links, in-layer links, and level-skipping links) and the non-hierarchical type (backward links) of links are observed. Nonetheless, the identification of such link types is somewhat arbitrary because it depends on the pre-assigned level ranks to nodes, which are often ambiguous. In many cases, there is no objective and definitive criterion according to which a node must be on a specific level, though experts with domain knowledge can give a level rank to a node based on their domain knowledge and subjective judgment. Such rank-assigning work based on domain knowledge is a usual practice in food web research (Dune et al, 2008) and industrial system research (Dalziel, 2007). Measures based upon such assignments of ranks thus have a partially arbitrary character.

Alternatively, the logic of ordering of levels can be based upon network structures. Nakano and White (2007) proposed two algorithms to identify levels in a pre-assumed hierarchical directed network, and noted that they are not unique. In chapter 2, I also explored several practical ways of assigning a level rank to each node in a directed network, using differently the information of the network positions of nodes in a directed network.

Regardless of which method is used and whether it is arbitrary, after each node is assigned a unique level rank, i.e. grouped into a specific level, we can identify if a local flow/link is from a lower level to a higher or the same level (hierarchical) or from a higher level to a lower level (non-hierarchical). More specifically, I differentiate all the links of network into four different types (also demonstrated in the examples in Figure A.1):

1) Regular: the link connects from a node on a pre-defined lower level (i) to a node on its adjacent higher level (i-1);
2) Level-Skipping: the link connects from a node on a pre-defined lower level (i) to a node on a level (j) higher than its adjacent higher level (i-1), i.e. $j < i-1$;
3) In-Layer: the link connects between nodes on the same level (i);
4) Backward: the link connects from a node on a predefined high level (i) to a node on a lower level (j), i.e. $i < j$.

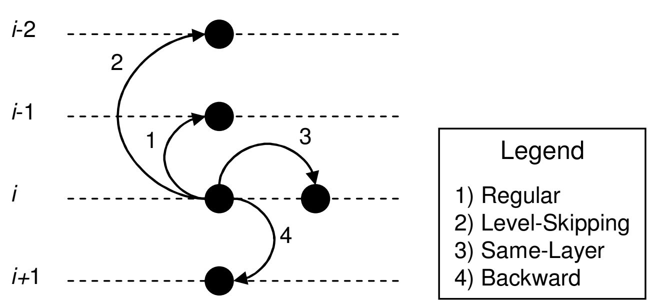

Figure A.1 Examples for four types of links identified according to levels

The first three types are accepted as hierarchical links, although intuitively there is an order for the hierarchy degree they represent, which is:

Regular > Level-Skipping > In-Layer

However, the fourth type, i.e. backward link, clearly violates the fundamental assumption that, in a pure flow hierarchy all flows/links follow one general direction, so it is non-hierarchical. Now we may count the ratio of hierarchical types of links over total links as a potential hierarchy metric,

$$h = \frac{m - \sum_{i=1}^{m} e_i}{m} \tag{A-1}$$

where m is the number of links in the network and e_i=1 if link i is a backward link (0 otherwise). However, because the "backward" vs. "forward" directions are relative, whether a link is backward or forward depends on the direction assumed. To make it simple, I assume that backward links are inconsistent to a system's dominant orientation, and are minor ones. Thus, at maximum only half of the links can be "backward", and the ratio calculated from formula A-1 will always range between 0 and 0.5. To improve this potential metric to range between 0 and 1, I normalize it to the range of [0, 1] by multiplying 2 to the term in A-1 which counts the backward links. Furthermore, when the same numbers of forward and backward links exist in a network, a reasonable hierarchy metric should be zero. However, in-layer links might exist so hierarchy degree is still larger than zero. To correct this and make the hierarchy degree zero when the forward and backward links are equal regardless of the in-layer links, I propose an improved formula from A-1,

$$h = \frac{m - 2 \times \sum_{i=1}^{m} e_i}{m} \tag{A-2}$$

where m is the total number of links. e_i=1 if link i is a backward link, e_i=0.5 if link i is a in-layer link, and e_i=0 if link i is either a regular or level-skipping link.

However, such an approach may <u>over count non-hierarchical links</u>. Here I use a simple example network (Figure A.2) of five nodes to examine the feasibility for identifying non-hierarchical links (vs. hierarchical links) based on the level ranks obtained from the five extreme algorithms introduced above. Nodes are placed on their corresponding levels given by the different algorithms shown in Chapter 2.3.

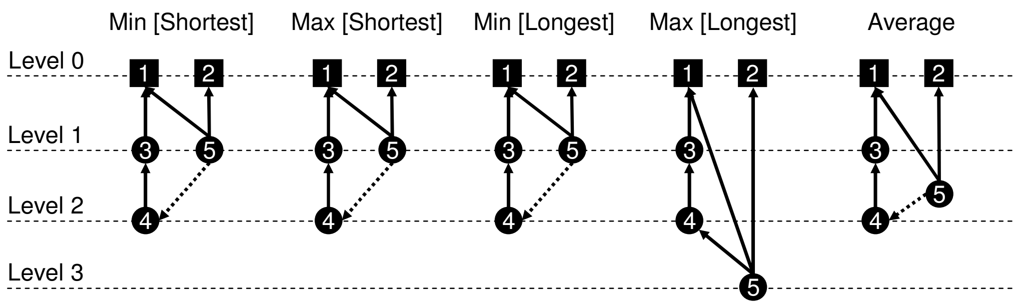

Figure A.2 Identifying nonhierarchical links based on five different level ranking algorithms. Non-hierarchical backward links are dashed.

In this network, there is one source node, 5, and two sink nodes, 1 and 2. Obviously, we can observe directly that all the links in this small network do follow a holistic direction from bottom to top, so are hierarchical (h =1 using the method in our paper). However, according to the Min [Shortest] and Max [Shortest] ranking algorithms based on counting the shortest paths, node 5 belongs to level 1, and node 4 belongs to level 2, then the link from node 5 to node 4 is a backward and nonhierarchical link. According to Min [Longest] algorithm that counts longest paths, because node 5 has its longest path to node 2 in the length of 1, it is still placed on level 1, and its link to node 4 is still a nonhierarchical one. The fifth algorithm uses the average path length to sinks as a node's level rank, then node 5 has three paths to the sinks and the average path length is 1.66. Node 4 has one path of length 2 to the sinks, so its level rank is 2. So, the link from node 5 to node 4 is again identified as a nonhierarchical one.

Only the *Max [Longest]* algorithm does not over count non-hierarchical links. As a matter of fact, this algorithm theoretically equates finding the layout of the Dependency Structure Matrix (DSM) of the directed network which minimizes the number of links (dependencies) above the diagonal, if we place the sinks at the left upper corner of the adjacency matrix. The other algorithms more or less ignore part of the global path information while Max [Longest] considers all the path information when it operates. In contrast, the Max [Longest] algorithm works appropriately because it has traced complete path information from the nodes to the sinks in the effort of assigning level ranks.

A.3 Hierarchy Metric based upon *Max [Longest]* Level Identification Algorithm

Therefore, I propose a second hierarchy metric based on counting the non-hierarchical links identified by the Max [Longest] level-ranking algorithm. Calculating this hierarchy metric consists of the following steps:

Step 1) Identify the sinks of the network as the benchmark. Alternatively, we can also use sources of the network as the benchmark.

Step 2) Calculate the lengths of the longest paths from each node to all the sinks, and use the longest one of these lengths as the node's level rank.

Step 3) Count the total number of the backward links. Any link, which goes from a node with higher level rank to a node with a lower level rank, is identified as a nonhierarchical link. The rest of the links are hierarchical.

Step 4) With the known information on the levels and link types, compute the hierarchical degree using formula A-2.

Figure A.3 lists the hierarchy degrees for several example networks based on this approach. A pure hierarchical structure, such as a tree (e.g. Figure A.3A), has a hierarchy degree 1. For a pure directed cycle (e.g. Figure A.3E), this approach does not give an answer, because there is neither a sink nor a source node to be used as a benchmark.

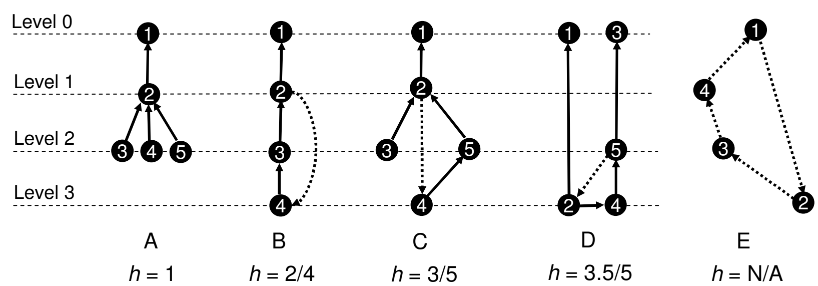

Figure A.3 Hierarchy degrees of example networks based on the *Max [Longest]* ranking algorithm. Non-hierarchical backward links are dashed.

Similar to the hierarchy metric proposed in the paper which counts the links on cycles, this alternative hierarchy metric also examines how much the intermediate or local links coherently follow a holistic direction in the directed network. A numerical experiment is conducted to compare how the two reasonable but different hieratical metrics differ in capturing the hierarchy degrees of random networks with varied degree of hierarchies, using the model presented in Chapter 4.

With this model, by tuning "transaction specificity" between 0 and 1, I am able to generate a series of random networks with varied but continuously-changing degree of hierarchy. The metrics are then used to calculate the hierarchy degrees of each random network generated using the model under the setting: n=30, k=2,3,4 (m =60,90,120), and s (Transaction Specificity) increasing from 0 to 1 with a step width 0.05. For each data point, 30 sample networks are generated to calculate the average hierarchy degree. The results in Figure A.4 show that the two metrics capture similar trends in the changes of hierarchy in response to randomization.

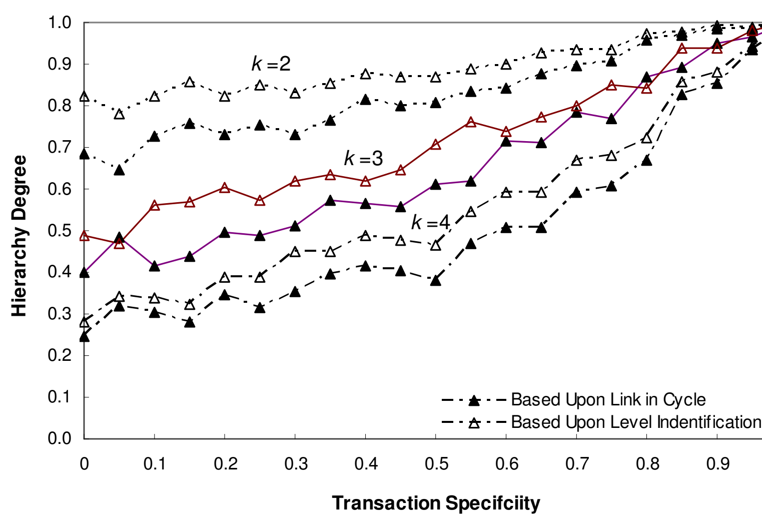

Figure A.4 Hierarchy degrees calculated using two different metrics

However, the second metric (based on level identification) has two disadvantages in practice, compared with the hierarchical metric (based upon link cycle identification) in the main text of this thesis. First, it requires extra steps to identify the sources or sinks. In some systems where neither sources nor sinks exist mathematically, the algorithm does not apply without arbitrarily picking the benchmark nodes. The second disadvantage is that, it is computationally hard to find the longest paths between nodes in a large network, such as the industrial network in this thesis with several hundreds of nodes and several thousands of links. Such calculation requires exhaustive search of paths of all possible lengths. It is doable if the network size is small enough. However, when the system size becomes big, it may take "forever" to calculate the level ranks.

Therefore, among these two hierarchy metrics and algorithms, we prefer the first hierarchy metric simply because of its ease of computation, although the second metric is also meaningful in computable cases.

Appendix B

Other Applications of Flow Hierarchy Measurement

The algorithm introduced in Chapter 3 was used to compute the hierarchy metric and z-score of a diverse set of empirical evolving self-organizing networks: the Bridge Brook Lake food web (Havens, 1992; Dunne, Williams and Martinez, 2002) and the Northeastern US Shelf food web (Link, 2002; Dunne, Williams and Martinez, 2004), Japanese producer-supplier networks in automotive and electronics production sectors (Dodwell Marketing Consultants, 1983, 1993, 2001), two biological information-processing networks including the synaptic connections between neurons in the nematode worm Caenorhabditis elegans (Milo et al, 2004) and developmental transcription network of Drosophila Melanogaster (Milo et al, 2004), the call networks of the kernels of two operation system software, Linux (Linux Kernel Organization, Inc. http://www.kernel.org/) and Apple computer's Mac OS X (Darwin) (Apple, Inc. http://www.opensource.apple.com/darwinsource/10.0/).

Table B.1 Hierarchy degrees of empirical networks and comparable random networks

Network	Type	*N*	*L*	*k*	h_{real}	h_{rand}	σ_{rand}	*z*-score
Bridge Brook Lake	Food Web	25	104	4.160	0.9809	0.0213	0.0338	28.39
NE US Shelf	Food Web	79	1378	17.443	0.8273	0	0	infinite
Japanese Automobile Industry	Economic	679	2437	3.589	0.9988	0.0601	0.0114	82.34
Japanese Electronics Industry	Economic	227	648	2.855	0.5957	0.1338	0.0310	14.90

C. elegans	Biological	280	2170	7.750	0.1171	0.0009	0.0018	64.56
D. melanogaster	Biological	107	301	2.813	0.3289	0.1308	0.0444	4.46
Darwin XNU-123.5	Software	646	4351	6.735	0.4872	0.0024	0.0021	230.86
Linux Kernel 1.1.70	Software	287	1385	4.826	0.8065	0.0159	0.0082	96.41

Each empirical network is compared to an ensemble of 1,000 randomly-generated networks with the same N and L (or k). I extracted the software call networks using the architecture analysis software Understand C++. In the call networks, a link from source code B to source code A exists if any function in A calls and relies on any function located in B. In the industry networks, a link from firm B to firm A exists if firm A procures any products from firm B.

Domain-specific knowledge is needed to understand the difference in hierarchy degree of empirical networks of the same type. In the results (Table B.1), there is no clear evidence to show that system types (e.g. biological vs. economic) differentiate networks in terms of flow hierarchy. But from a network science perspective, the results show all of these typical empirical networks exhibit stronger hierarchical architectures than comparable random networks with the same sizes and average degrees, indicating the emergence of hierarchy as a significant feature of real-world evolving self-organizing networks.

This indicates that ***evolution*** (e.g. the extent to which the system has evolved), compared to typology, might be a more fundamental determinant of the hierarchical degrees of self-organizing networks. Simon (1962) first hypothesized that hierarchy emerges inevitably through a wide variety of evolutionary processes because hierarchical structures are stable (Simon, 1962; Agre, 2003). However, quantitative evidence on hierarchy, either containment or flow hierarchy, over the course of system evolution has not been reported previously, largely due to the lack of an appropriate measure. The hierarchy metric and technique in the present paper allows the exploration of this fundamental question that links hierarchy and system evolution.

I calculated the hierarchy metrics of the call networks of various historical versions of the Linux kernel from its origin, version 0.01 to 2.3.0. The Linux kernel is an open source system developed by self-organized contributors around the world. As indicated in Figure B.1A, the hierarchy degree and corresponding *z*-score (Figure B1.B) of the Linux kernel have been generally increasing over its life cycle. The first version (0.01) was built and released by a single person. After that, many people contributed subroutines to the project, and thus hierarchy degree declined for a little while. During the most of its life as an open-source system, the hierarchy degree has increased as the self-organizing system grows, stabilizes, and matures, as Simon (1962) argued. The observation of a general increase of k as the system evolves (Figure B.1C) affirms the hierarchical tendency of this system since increases in k alone would work to decrease the hierarchical metric.

Network decompositions (Clauset, Moore, Newman, 2008, Sales-Pardo et al, 2007, Girvan and Newman, 2002, Guimera, Sales-Pardo and Amaral, 2007; Newman, 2006; Leicht and Newman, 2008) may reveal certain underlying architectures and interesting methods (Girvan and Newman, 2002, Guimera, Sales-Pardo and Amaral, 2007; Newman, 2006; Leicht and Newman, 2008) to detect modularity have been developed recently. I also calculated the optimal modularity of the Linux kernel networks, using Newman's eigenvector-based algorithms for both undirected (Newman, 2006) and directed networks (Leicht and Newman, 2008), and found unclear trends, if not slightly decreasing, in terms of modularity during the same period of time. No theoretical or observational indication has been found about how modularity of self-organizing networks should change in evolutionary processes. Compared to the flow hierarchy degree, the usefulness of modularity in terms of tracking the evolving patterns of self-organizing networks appears limited.

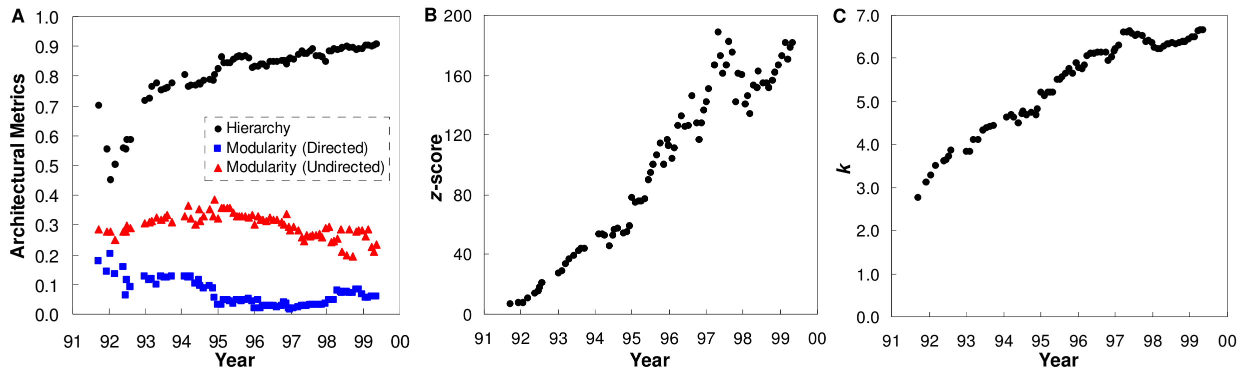

Figure B.1 Longitudinal evolution of Linux kernel.

(A) hierarchy degree and modularity. (B) *z*-score. (C) average degree. At least one data point is included for each month when there are multiple releases in a month. For some months, no data point is included because there were no versions either released or available in the online archive. See Supporting Information for more details of the data and results. 1,000 randomly-generated comparable networks are used to calculate h_{rand} and z-score for each data point. Because hierarchy degrees of random networks do not vary significantly with the increases of n when $k > 2$ and $n > 80$ (see Figure 3.6B in the main text), to reduce computation efforts I use randomly generated networks with a constant n (=100) and corresponding k to predict h_{rand} and z-scores for most of the data points with large n, except the earliest 8 ones with less than 100 nodes. For the earliest 8 data points, the random networks have the same n and L of their corresponding actual networks.

Both flow hierarchy and modularity are essentially static (and architectural) rather than temporal concepts (Simon, 1962). So the change of flow hierarchy degree and the non-change of modularity of Linux Kernel over time may indicate some important intrinsic mechanisms on network growth. Further research is needed to explore such mechanisms.

In fact, this metric of flow hierarchy potentially provides a way to characterize and detect different structural regimes of discrete systems with a potential direction, analogical to the different regimes of the continuous fluid flows. For example, the networks A and B in Figure

B.2 are strictly hierarchical (uni-directional) and analogical to the “laminar flow” regime of fluid flows. In network C of Figure B.2, some of the local links are involved in cycles (analogical to eddies or vortexes of fluid flows). The system is no longer purely hierarchical and is in a “transitional flow” regime. In network D, all the links are involved in cycles, so this case is analogical to the “turbulent” regime of fluid flows.

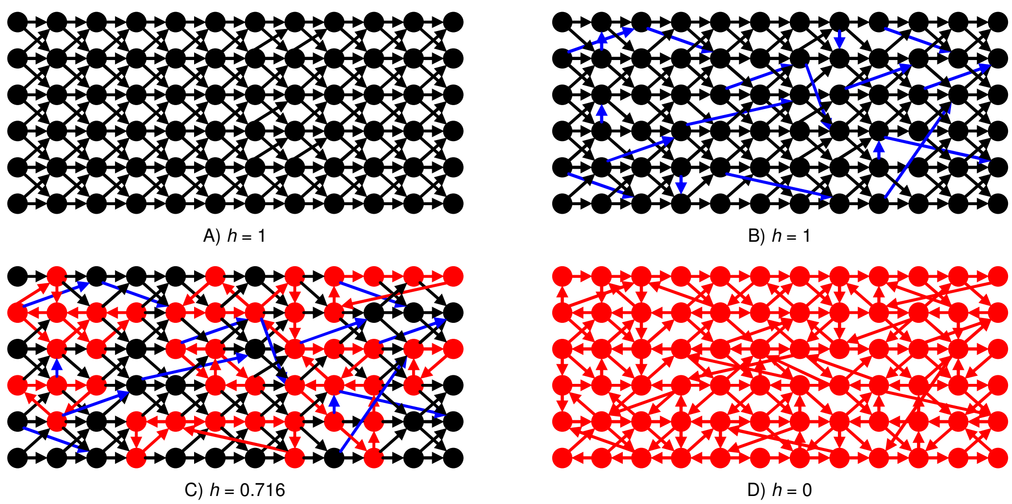

Figure B.2 A network with 72 nodes and 176 directed links, with links varied toward different directions in four scenarios.

Note: The links in blue color in B) and C) either skip levels or connect between nodes in the same level. Such links add complexity and the difficulty to determine the levels and ranks, but do not destroy the overall network directionality, i.e. flow hierarchy. The nodes and links colored in red are involved in cycles.

Thus, as the Reynolds Number (Reynolds, 1883) characterizes different flow regimes, such as laminar, turbulent or transitional flow, the flow hierarchy metric may also potentially characterize the structural regimes of discrete network systems, such as industries, food webs and software. Like the contribution of Reynolds Number for the development of the overall field of fluid mechanics, the flow hierarchy metric may also potentially provide great value for designing and managing complex network systems, but further research is needed.

In general, the hierarchy metric (as well as the *z-score*) explores a commonly observed but theoretically ignored form of hierarchy in networks -- flow hierarchy, and may open the way to objectively compare hierarchies of different networks, identify the structural regime of a network, detect the evolutionary stages of a single network, and compare the evolving patterns of different networks. I anticipate the hierarchy metric and measurement technique to be applied to more systems, such as ecological, biological, brain and neural, social and technological systems, and to help understand better their domain-specific architectures and evolutionary patterns.

Acknowledgement for Appendix B

For this part of research included in Appendix B, I thank Jennifer Dunne for providing the food web data, Ron Milo for providing the biological network data, and Kevin Groke for technical support to extract the call networks of software packages.

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Appendix C

Alternative Representations of the Simulation Results: Numerical Table and 3D Figure

Here I provide two representations of the simulation results, alternative to Figures 4.4 and 4.5.

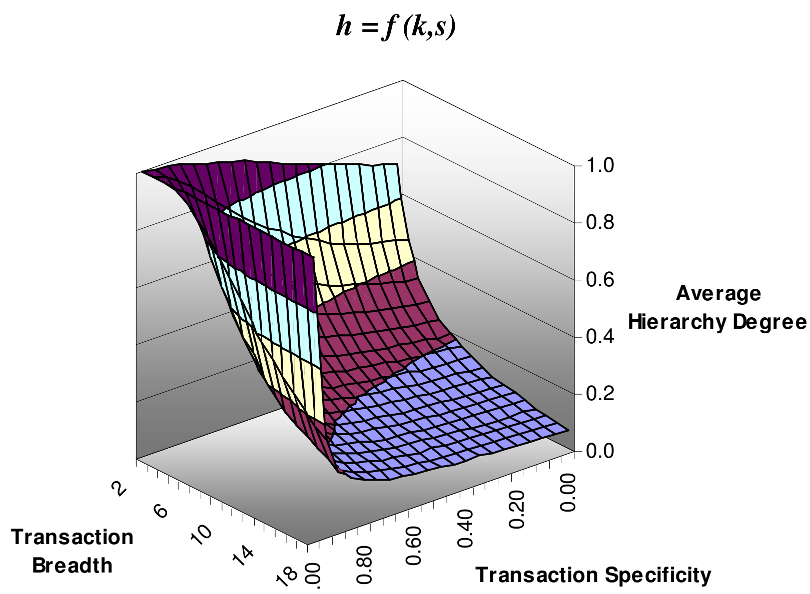

Figure C.1 Average Hierarchy Degree

Table C.1 Average Hierarchy Degree

k	Specificity																				
	0.00	**0.05**	**0.10**	**0.15**	**0.20**	**0.25**	**0.30**	**0.35**	**0.40**	**0.45**	**0.50**	**0.55**	**0.60**	**0.65**	**0.70**	**0.75**	**0.80**	**0.85**	**0.90**	**0.95**	**1.00**
2	0.711	0.725	0.738	0.757	0.771	0.789	0.809	0.821	0.839	0.854	0.876	0.894	0.912	0.925	0.938	0.950	0.964	0.977	0.986	0.993	1
3	0.463	0.480	0.485	0.501	0.517	0.531	0.547	0.573	0.594	0.620	0.653	0.674	0.712	0.747	0.789	0.833	0.875	0.917	0.954	0.980	1
4	0.348	0.354	0.368	0.376	0.391	0.405	0.418	0.435	0.456	0.477	0.496	0.525	0.557	0.596	0.635	0.683	0.751	0.821	0.898	0.958	1
5	0.285	0.294	0.301	0.308	0.320	0.327	0.340	0.352	0.367	0.380	0.404	0.430	0.453	0.483	0.525	0.570	0.638	0.725	0.833	0.928	1
6	0.242	0.250	0.254	0.259	0.269	0.277	0.288	0.298	0.310	0.323	0.337	0.355	0.379	0.403	0.436	0.475	0.536	0.621	0.746	0.893	1
7	0.211	0.212	0.223	0.229	0.234	0.241	0.250	0.256	0.268	0.276	0.292	0.307	0.324	0.349	0.371	0.411	0.466	0.540	0.657	0.848	1
8	0.187	0.193	0.195	0.202	0.206	0.213	0.224	0.227	0.235	0.241	0.257	0.266	0.283	0.304	0.325	0.358	0.401	0.473	0.596	0.792	1
9	0.167	0.171	0.176	0.178	0.183	0.193	0.196	0.204	0.210	0.216	0.229	0.232	0.250	0.267	0.286	0.318	0.354	0.415	0.523	0.746	1
10	0.151	0.155	0.158	0.164	0.167	0.170	0.177	0.184	0.189	0.196	0.202	0.216	0.222	0.239	0.255	0.282	0.315	0.369	0.477	0.685	1
11	0.138	0.143	0.144	0.147	0.152	0.157	0.161	0.167	0.173	0.180	0.185	0.192	0.204	0.215	0.233	0.253	0.279	0.329	0.416	0.627	1
12	0.126	0.127	0.133	0.135	0.140	0.142	0.148	0.152	0.155	0.160	0.170	0.175	0.185	0.193	0.214	0.230	0.253	0.300	0.374	0.576	1
13	0.116	0.119	0.124	0.125	0.128	0.131	0.133	0.142	0.143	0.149	0.156	0.165	0.170	0.179	0.195	0.212	0.235	0.268	0.334	0.529	1
14	0.110	0.112	0.114	0.116	0.118	0.123	0.127	0.129	0.134	0.137	0.141	0.148	0.157	0.166	0.176	0.190	0.209	0.249	0.306	0.489	1
15	0.100	0.103	0.104	0.106	0.109	0.112	0.116	0.121	0.123	0.129	0.135	0.139	0.144	0.157	0.165	0.177	0.194	0.223	0.287	0.447	1
16	0.095	0.095	0.101	0.100	0.103	0.105	0.110	0.113	0.115	0.121	0.122	0.129	0.135	0.144	0.155	0.163	0.180	0.207	0.263	0.409	1
17	0.089	0.091	0.091	0.094	0.096	0.098	0.100	0.103	0.107	0.111	0.115	0.118	0.125	0.132	0.144	0.152	0.169	0.190	0.244	0.374	1
18	0.082	0.085	0.086	0.089	0.090	0.094	0.096	0.100	0.101	0.104	0.109	0.114	0.117	0.124	0.130	0.143	0.157	0.178	0.220	0.348	1

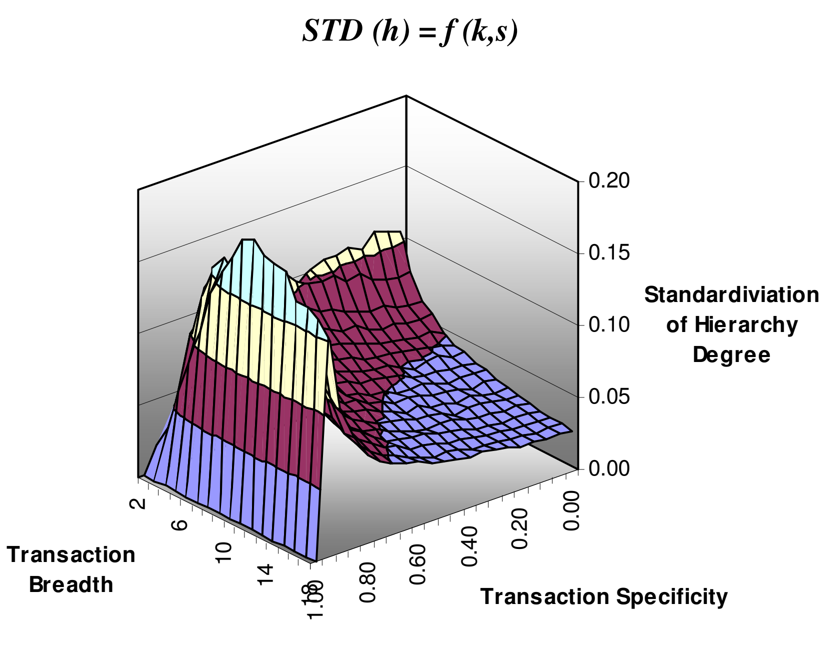

Figure C.2 Standard Deviation of Hierarchy Degree

Table C.2 Standard Deviation of Hierarchy Degree

	Specificity																				
k	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
2	0.107	0.110	0.112	0.103	0.108	0.106	0.106	0.102	0.096	0.093	0.086	0.083	0.077	0.068	0.065	0.055	0.043	0.033	0.023	0.018	0
3	0.082	0.081	0.083	0.086	0.093	0.091	0.098	0.098	0.099	0.103	0.114	0.109	0.115	0.120	0.116	0.108	0.096	0.077	0.059	0.033	0
4	0.065	0.066	0.068	0.072	0.070	0.074	0.077	0.081	0.083	0.090	0.092	0.097	0.108	0.113	0.121	0.132	0.130	0.129	0.100	0.063	0
5	0.061	0.060	0.060	0.064	0.063	0.066	0.071	0.070	0.075	0.080	0.084	0.086	0.093	0.096	0.115	0.125	0.136	0.142	0.130	0.086	0
6	0.051	0.055	0.054	0.056	0.058	0.059	0.063	0.066	0.068	0.071	0.076	0.078	0.084	0.093	0.100	0.109	0.125	0.144	0.153	0.112	0
7	0.046	0.049	0.051	0.052	0.054	0.057	0.057	0.059	0.063	0.065	0.068	0.076	0.077	0.087	0.093	0.102	0.115	0.143	0.164	0.142	0
8	0.045	0.045	0.049	0.049	0.046	0.050	0.055	0.055	0.057	0.061	0.063	0.068	0.070	0.079	0.085	0.094	0.109	0.133	0.157	0.161	0
9	0.041	0.043	0.043	0.045	0.045	0.048	0.051	0.054	0.055	0.055	0.060	0.062	0.068	0.071	0.077	0.085	0.101	0.120	0.150	0.175	0
10	0.041	0.041	0.042	0.041	0.043	0.046	0.046	0.047	0.051	0.051	0.055	0.058	0.067	0.069	0.073	0.084	0.100	0.114	0.146	0.191	0
11	0.037	0.039	0.036	0.040	0.042	0.043	0.046	0.047	0.046	0.050	0.053	0.058	0.059	0.066	0.072	0.078	0.089	0.104	0.143	0.195	0
12	0.036	0.035	0.036	0.039	0.037	0.040	0.041	0.045	0.043	0.048	0.050	0.055	0.057	0.060	0.070	0.070	0.083	0.102	0.130	0.187	0
13	0.034	0.034	0.036	0.037	0.039	0.035	0.041	0.042	0.042	0.045	0.048	0.050	0.053	0.059	0.066	0.073	0.083	0.097	0.124	0.185	0
14	0.033	0.034	0.033	0.035	0.034	0.037	0.040	0.040	0.040	0.041	0.044	0.047	0.052	0.054	0.060	0.069	0.076	0.095	0.116	0.183	0
15	0.031	0.031	0.032	0.032	0.033	0.034	0.037	0.039	0.040	0.044	0.044	0.045	0.048	0.054	0.060	0.065	0.072	0.084	0.118	0.167	0
16	0.030	0.030	0.031	0.032	0.033	0.033	0.035	0.037	0.037	0.040	0.041	0.043	0.048	0.050	0.055	0.063	0.070	0.084	0.113	0.166	0
17	0.029	0.030	0.029	0.031	0.031	0.033	0.033	0.034	0.036	0.038	0.037	0.041	0.044	0.048	0.052	0.057	0.066	0.076	0.104	0.162	0
18	0.027	0.029	0.029	0.031	0.029	0.032	0.035	0.035	0.034	0.037	0.039	0.040	0.045	0.046	0.049	0.054	0.062	0.076	0.097	0.152	0