Abstract Number: 015-0985

Measuring and Understanding Hierarchy as an Architectural Element in Industry Sectors

Jianxi Luo*
Massachusetts Institute of Technology
77 Massachusetts Avenue E38-448, Cambridge, MA 02139
Email: luo@mit.edu
Phone: +1 (617) 642-1652

Daniel E. Whitney
Massachusetts Institute of Technology
77 Massachusetts Avenue E40-243, Cambridge, MA 02139
Email: dwhitney@mit.edu
Phone: +1 (617) 253-6045

Carliss Y. Baldwin
Harvard Business School
Soldiers Field, Boston, MA 02163
Email: cbaldwin@hbs.edu
Phone: +1 (617) 495-6673

Christopher L. Magee
Massachusetts Institute of Technology
77 Massachusetts Avenue E38-450, Cambridge, MA 02139
Email: cmagee@mit.edu
Phone: +1 (617) 252-1077

* Corresponding author

POMS 21st Annual Conference
Vancouver, Canada
May 7 to May 10, 2010

Abstract

Classic supply chains display strict hierarchy, whereas clusters of firms have linkages going in many different directions. Previous theory has assumed the existence of the hierarchical relationships among firms in production sectors, and empirical work has focused on single industries or bilateral relationships. However, quantitative evidence on the hierarchy in large industrial sectors is lacking. In this paper, we define and develop the metrics and methods on the degree of hierarchy in transactional relationships among firms, and apply them to two sectors in Japan: automotive and electronics. We compiled the networks of firms connected by supply-procurement transactional relationships. Our empirical analysis shows that the electronics sector exhibits a lower degree of hierarchy than the automotive sector due to the wide existence of supply cycles. Then, using a network simulation model to relate sector-level hierarchy to firm-level transaction specificity, interview data and existing knowledge on product technologies, we propose a theory to explain how the nature of technologies may influence the structure of supply transactions, which in aggregate determine overall industrial hierarchy.

Keywords: sector, industry architecture, networks, hierarchy, modularity, transaction specificity

1 Introduction

Hierarchy is a generic structure in which levels are asymmetrically ordered. In an industry setting, classic supply chains display strict hierarchy, whereas clusters of firms have linkages going in many different directions. Previous theory has often assumed the existence of the hierarchical relationships among firms and empirical industry studies tend to focus on a single-layer industry, or a two-layer structure comprising buyers and suppliers. And yet, some industries have a multi-layer structure with a multi-step supply chain. Others comprise a cluster of complementary firms producing different parts of a large system. In this paper, we use network analysis[1] to study multi-layer industries both empirically and theoretically. Our research method is relevant to the prior work in social network analysis (Wasserman and Faust, 2004) and particularly related the work on roles and positions started by White et al (1976).

Previous studies in the industrial economics tradition have investigated industry structures in terms of vertical integration and dis-integration (Nishiguchi, 1994; 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. These studies on vertical integration focus on the division of labor between two groups, customer and supplier, but do not address multiple supplier/customer layers, nor the possibility that numerous complementary goods will be combined into large systems. This micro-analytic emphasis has led to the relative neglect of an important fact – the

---

[1] For an overview of work in network analysis methods, see (Newman, 2003).

firms across related industries co-evolve, and many of their economic activities, including innovation, development and production of the end-user products or service, do not happen just between firms within a single stable industry, but throughout the dynamic value chains, or value networks (Jacobides, 2005; Jacobides and Winter, 2005; Christensen and Rosenbloom, 1995).

This paper takes an industry sector, i.e., a group of industry layers, as the unit of analysis. Following Malerba (2002) we use the term "sector" to mean a network of firms in different sub-industries, which supply complementary goods for making a set of system products. For example, an automobile sector includes system integrators, sub-system integrators, component suppliers and materials suppliers that are involved in the making of automobiles. To avoid confusion, we 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 relationships may connect the firms in a sector, such as alliances, joint ventures, competition. In this paper, we investigate transactional relationships, i.e., the transactional exchanges of components and parts for making the final product.

This research follows the definition of "industry architecture" from Jacobides et al (2006) as the stable but evolving relationships along the value chain, i.e. the patterns in which labor is divided in a sector between different types of industry participants, and the associated set of "rules and roles" that emerge (Jacobides, Knudsen, and Augier, 2006)[2]. The notion of industry architecture considers the overall template that describes the distribution of labor among a set of co-specialized firms across a set of industries. Thus, the necessary level of analysis on industry

---

[2] "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".

architectures is the network of firms across the complementary industries in a sector. The analysis of industry architectures may provide opportunities to ask new and important questions on firm behaviors and performances, 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 the sectors differ in terms of their technological bases, innovation patterns, economic behaviors and performances, and the correlations, etc (Nelson and Winter, 1982; Dosi, 1988; Malerba and Orsenigo, 1993, 1996; 1997; Jacobides, 2006; Castellacci, 2007). However, our understanding is still limited concerning how sectors differ in terms of their architectures, and the technological and economic mechanisms that cause such differences. The present article seeks to objectively measure and compare a key aspect of industry architectures across sectors based on empirical data. It then proposes a theoretical explanation of how the technological base of a sector influences the structure of transactions inside the sector and thus the hierarchical aspect of its architecture.

Studies of industrial sectors often observe or suggest a hierarchical architecture (Coase, 1937; Malerba, 2002; Dalziel, 2007), in which production processes are organized into sequential stages (Coase, 1937; Abernathy, Clark and Kantrow, 1983)[3]. Firms that perform higher level tasks depend upon firms that perform lower level tasks (Dalziel, 2007). Such hierarchy does not exist in a pure market such as a stock market, where traders can buy from and sell to any other trader. In an industrial sector, a firm may also perform multiple industry roles in different

---

[3] 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, 2006).

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. Robust methods to measure the patterns of industry architectures, in particular how hierarchical an industrial sector is, need to be developed. This research addresses these challenges.

Our methods and analysis differ from traditional institutional economics in four fundamental ways. First, the unit of analysis is a sector, instead of a narrower industry. Second, we examine macro industry architectures rather than the relationship between two industry layers. Third, we view and model an industry sector as a network of manufacturers and suppliers, and conduct quantitative network analysis. Four, we define the *degree of hierarchy* of a sector, but allow for non-hierarchical industry architectures.

Below, we will introduce an algorithm that quantitatively measures and compares the degree of hierarchy in different industry sectors[4]. We apply these measures to two comparative cases: the Japanese automotive and electronics sectors. In order to explore the mechanisms underlying the empirical observations, we use an analytical network model to generate a wide spectrum of sector-like random networks lying between two extreme scenarios: a pure random network and a hierarchical random network. The model incorporates two causal factors, transaction breadth and transaction specificity, which interact to influence the degree of hierarchy in the directed network. Transaction breadth is the number of transactional relationships that a firm enters into. Transaction specificity represents how specific a firm's transaction relationships are with respect

---

[4] The algorithm, the metric and their application to a wide range of directed networks is described fully in Luo and Magee (2009). In this paper, the algorithm and metric are shown in more detail for the case of industry architectures.

to potential market niches (Burt and Talmud, 1993). With the results from the empirical measurement, the model and semi-structured interviews, we then conduct a micro-level causal analysis with the comparison of the two empirical industrial sectors, centered on transaction cost economics (Coase, 1937; Williamson, 1975; 1981; 1985; Baldwin, 2008), in order to theoretically explain how hierarchy in industrial sectors may be collectively determined by technological and economic forces.

This research integrates concepts and methods from institutional economics, industrial economics, economic sociology, network sciences and systems engineering. For academics, it aims to provide a quantitative methodology for analyzing hierarchy as an architectural element in industry sectors. This methodology will allow more exploratory work to be done 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. The application of network analysis permits institutional economics to be extended from the structure of an industry to the architecture of a sector comprising several industries.

For industry practitioners, this research suggests that industry architectures may follow partially predictable patterns which are largely determined by the nature of the underlying fundamental technologies and the architectures of products produced in the sector. A better understanding of industry architectures in turn can guide companies in identifying opportunities and adopting strategies that are appropriate for the architecture and evolutionary status of the sector.

The remainder of the article is organized as follows. Section 2 below introduces the hierarchy typology, defines the type of hierarchy crucial for industry architectures, and summarizes the metric and algorithm used to quantify and measure hierarchies. Section 3 introduces transaction breadth as one factor that influences the degree of hierarchy of an industrial sector. Section 4 introduces data and the empirically measured hierarchy degree and transaction breadth. Section 5 introduces the analytical model that generates stochastic sector-like networks, and analyzes the results of a simulation experiment. Section 6 considers technological mechanisms that might explain the empirical and analytical results. Section 7 concludes.

2 Hierarchy in Industry Architecture

In practice, analyzing hierarchy by objective measurements is difficult for two reasons. First, hierarchy appears in various forms, hence the term has different meanings in different contexts. Second, real systems may not be "pure" hierarchies in a theoretical sense, and thus it is necessary to develop measures of the deviation between an actual system and some theoretical ideal hierarchy.

In this section, we first introduce a generalized definition of hierarchy and identify different types. We then focus on a particular type - a "flow hierarchy", which characterizes transactional relationships between industrial firms. Finally we present a way to measure how much a given industrial sector deviates from the standard of a pure flow hierarchy, based upon a recently developed metric for measuring hierarchy in general directed networks (Luo and Magee, 2009). In subsections from 2.1 to 2.3 we present the details on how the metric was originally developed and grounded, in order to allow the readers to fully understand the later sections on its specific application to industry architecture analyses.

2.1 Typology of Hierarchy

A hierarchy is a generic structure, in which levels are asymmetrically ranked according to a specific type of relation. Two types of hierarchies are useful for understanding network architectures: **containment hierarchy** and **flow hierarchy**.

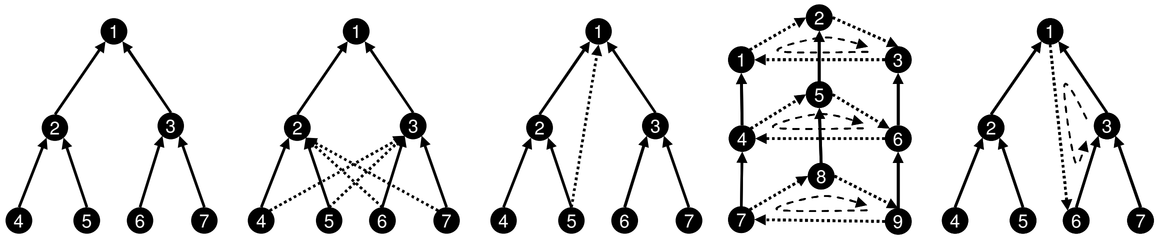
A containment hierarchy is similar to the concepts of "nested hierarchy" (Ahl and Allen, 1996; Simon, 1962; Christensen and Rosenbloom, 1995; Tushman and Murmann, 1998; Murmann and Frenken, 2006) and "hierarchy of inclusion" from Wilson (1969) (Murmann and Frenken, 2006). In a containment hierarchy, 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. For example, if B purchases a good from A, the good flows from A to B. The order of stages is essentially determined by the direction of the flows of goods, energy, materials, payments, or information. Other clear examples of a flow hierarchy include food webs and software routine networks. In a food web, energy flows. In a software routine network, it is information that flows as subroutines feed parent routines. A flow hierarchy can be described in terms of a network of nodes and directed links. A classic supply chain is a flow hierarchy in which components and parts flow from upstream suppliers to downstream manufacturers, and ultimately to users.

However, the transactions or supply 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 connecters, 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 aspect of industry architecture that we are seeking to investigate both empirically and theoretically.

2.2 Representing Flow Hierarchies as Networks

In this section, we use several simple examples first developed in Luo and Magee (2009) to represent the pure and impure existences of flow hierarchy in 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 1A.



A) Pure tree:
regular link

B) Mixed tree:
regular link

C) Mixed Tree:
level-skipping or in-layer link

D) Layers:
in-layer link

E) Cycles:
backward link

Figure 1 Generic structure and generic links in example networks (after Luo and Magee, 2009)

The first variant from the pure tree hierarchy arises when a node has multiple inbound and outbound links, as demonstrated by Figure 1B. We 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 1A and 1B are all “regular links”.

In the third case shown in Figure 1C, a link may skip its adjacent pre-indentified level. We call this a “level-skipping” link. The network in Figure 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 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.

Networks often exhibit layered structures as shown in Figure 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 1E, a link connects from a pre-identified higher level backward a lower one, i.e., a cycle emerges in a network. This violates the fundamental principle that, in a flow hierarchy things move in one general direction.

In the examples in Figure 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, the identification of these link types is arbitrary and depends on pre-assigned level ranking. A more consistent way to identify the network’s hierarchical degree is to decompose the network into such structures as tree and cycle, which are fundamental generic structures and can be identified without arbitrary level ranking. In particular, tree and layer are regarded as hierarchical structures, while a cycle is not (Moses, 2004) because it violates our hierarchy definition.

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 hierarchy architecture. On this basis, previous ways of defining hierarchy are of limited value. In the next section we 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.

2.3 Metric for Flow Hierarchy

A qualified hierarchy metric must be unambiguous in differentiating the hierarchical components and non-hierarchical components in order to measure how hierarchical an industrial network system is. If we choose to measure hierarchy by identifying hierarchical and non-hierarchical links, a predefined ordering of levels is required. However, in many cases, level order is 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 deterministic.

Accordingly, we propose a hierarchy metric (*h*) that measures the extent to which all the local flows follow a consistent "underlying direction". *The hierarchy metric is calculated as the percentage of links that are* ***not*** *included in any cycle* (Luo and Magee, 2009). 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. In the present paper, we will focus on unweighted networks.

Hierarchy degrees for several typical example networks are calculated and shown in Figure 2. The dashed lines indicate cycles.

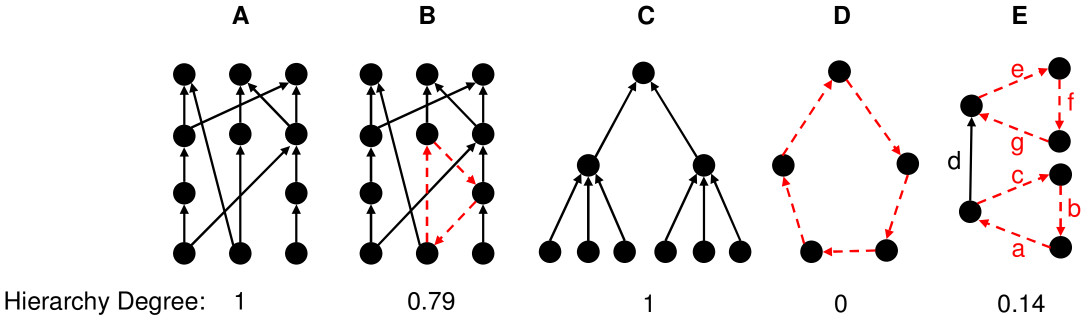


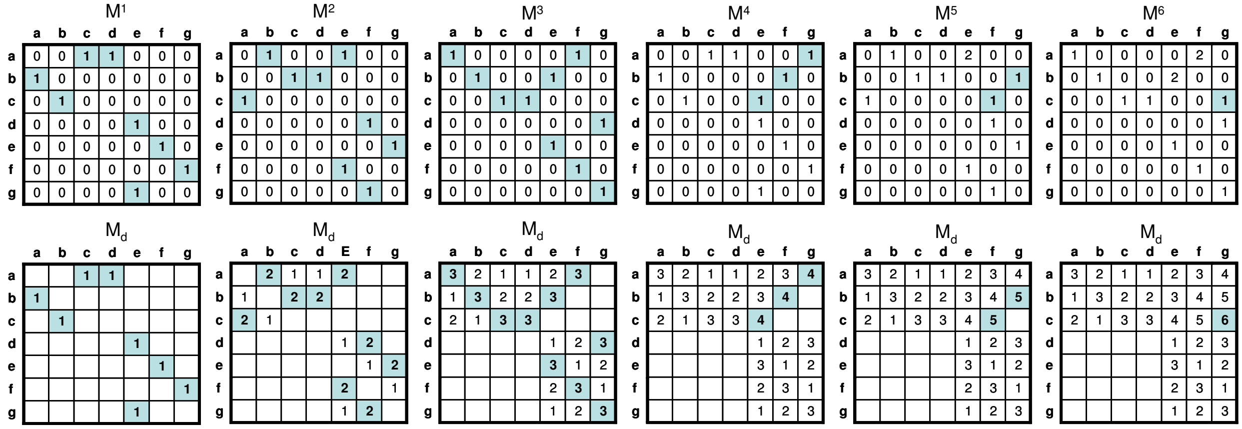
Figure 2 Example networks and corresponding hierarchy degrees (after Luo and Magee, 2009)

Networks A and B in Figure 2 are used to demonstrate the correlation between the overall system direction and local cycles in a directed network. In network A, all flows proceed in one general direction, no cycle exists, and *h*=1. Network B is almost the same as A, but has two extra links, which cause a cycle. 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 algorithm we use to calculate the hierarchy metric is as follows: First, we construct the link adjacency (LA) matrix of the original network. We name the cell (i,j) in the LA 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, we raise LA matrix's power p to find the link distance matrix M_d. We 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 LA, 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 *n*, the total number of nodes (equal to the length of the longest possible cycle of links). We leave d_{ij} empty if the end of link i is neither directly nor indirectly connected to the start of link j.

Fig. 3 below illustrates the process to derive the link distance matrix for the layered network in Fig. 2E. We pair M^p and the M_d with the state of knowledge after p steps. M^1 is the LA matrix for the network in Fig. 2E. 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^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^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^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^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^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			**1**	**1**			
b	**1**						
c		**1**					
d					**1**		
e						**1**	
f							**1**
g					**1**		

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_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_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_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_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 Derivation of link distance matrix by raising power of link adjacency matrix (after Luo and Magee, 2009)

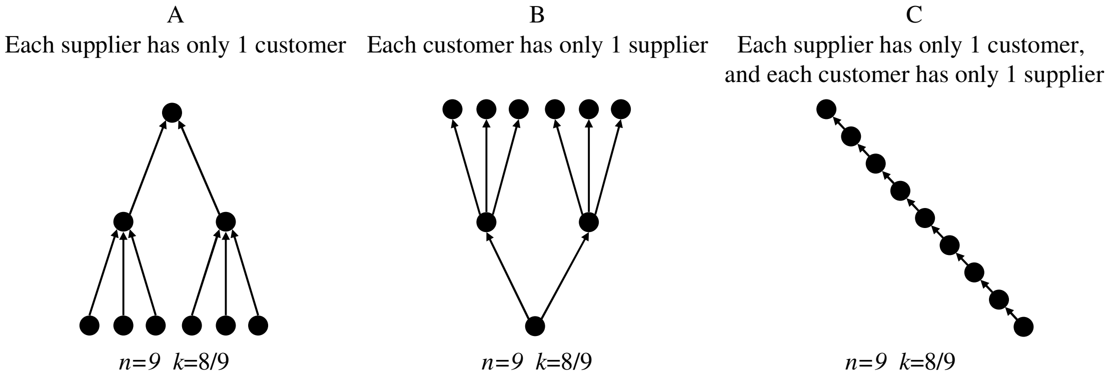
Given the link distance matrix, we are able to judge if a link is on any directed cycle by looking at values on the main diagonal. If d_{ii} is empty, then link i is not involved in any cycle. On the diagonal of the final link distance matrix in Fig. 3, only d_{dd} is empty, so only link d is not involved in any cycle. This agrees with our direct observation in the layered network in Fig. 2E. Thus this network's flow hierarchy degree is 1/7.

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 this metric, its wide applications, and an assessment of alternative metrics, see Luo and Magee (2009). In this paper, we will focus on its use in analyzing industrial networks.

3 Transaction Breadth

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, we 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 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 tree (example shown in Figure 4A). 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 4B), 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 4C), and k is still equal to $(n-1)/n$.


A
Each supplier has only 1 customer

B
Each customer has only 1 supplier

C
Each supplier has only 1 customer, and each customer has only 1 supplier

Figure 4 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" of 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 4, 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.

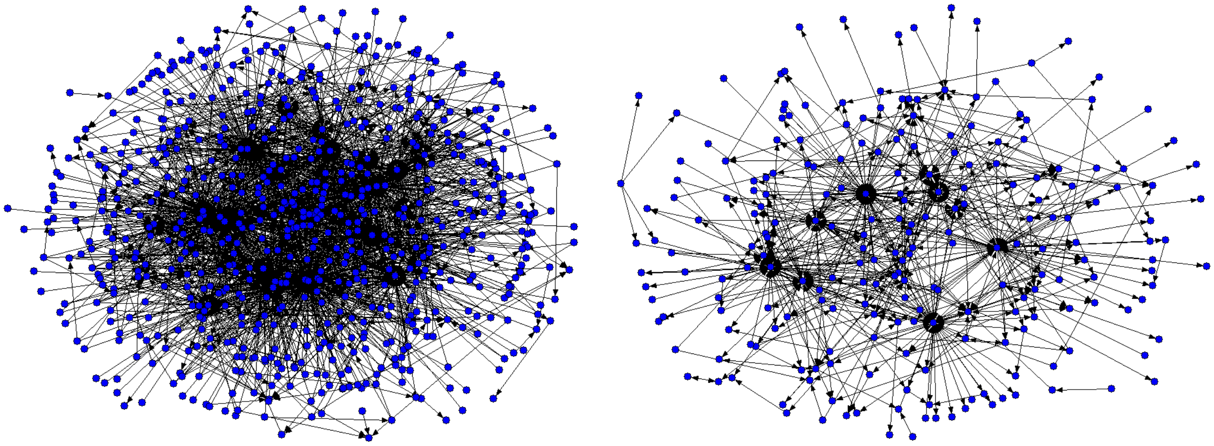
4 Data and Empirical Measurements

In our exploratory study, we 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.

We 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. We 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.

For each industrial sector at a specific year, we 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 5 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. It is not surprising but important that such visualization tools while useful do not allow one to see very significant differences in hierarchy. For that, the metric introduced in section 2 must be applied to these networks.



A) Automotive Sector B) Electronics Sector

Figure 5 Japanese sectoral supply networks in 1993

Table 1 summarizes the network descriptive statistics of the compiled network data, as well as the calculated transaction breadth (*k*) and hierarchy (*h*) 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 hierarchical (0.9988) than the electronics production sector (0.5957). And, the hierarchy degrees of the automotive sector in Japan did not change much and remained high from the early 1980s to the early 2000s. In fact, only one or two small supply cycles were found in the automotive industrial networks from 1983 to 2001.

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. Therefore, 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. In the later sections, we use a mixed strategy, including the simulation model, company interviews, and technical analysis of the products, to explain the observed difference in hierarchy degree of the two sectors.

Table 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)	0.9973	0.9988	0.9991	0.5957
Cycle Tracking	two 2-node cycles	one 3-node cycles	one 2-node cycle	many

5 Industrial Network Model

Industry architecture is essentially the collective result of the local decisions and behaviors of individual firms on their transactional links with other firms. In the previous sections, we have empirically calculated the hierarchy degree and transaction breadth of two different industrial networks, and observed their differences. In this section, we will introduce a random network model to relate the macro pattern, e.g. hierarchy, to micro patterns of connection at the level of individual firms, and analyze how firm-level factors may interact and lead to different degrees of hierarchy in an industrial sector.

5.1 Model Description

In this section, we develop a model that builds on two idealized rules of market structures: hierarchy (Coase, 1937; Simon, 1962) and niche (Burt and Talmud, 1993; Podolny at al, 1996). The niche models in turn depend upon social network models of roles (Wasserman and Faust, 1994; White et al., 1976). We build our model in such a way to describe how the hierarchy (h) of an industrial network 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. It equals the average number of unique suppliers each firm has in a given network. It is measurable, and is the same as *k* in the NK framework (Kauffman, 1993; Rivkin and Siggelkow, 2002) and is the average nodal degree in network analysis (Newman, 2003).
3) *s* (Transaction Specificity): The degree to which a firm's transactional links are constrained to a specific set of similar firms (discussed below).

Our network model is built on two extremes according to connection pattern: a pure random network and a hierarchical random network. For networks of a given size, *n*, and transaction breadth, *k*, by varying a key parameter, *s*, we can systematically create mixtures of these two polar extremes, weighted to one extreme or the other. This in turn will allow us to discover the mathematical relationship between the degree of hierarchy, *h*, and the causal parameters, *n*, *k*, *s* in the generated random networks. By inverting this relationship, we can then infer the unobservable variable *s*, i.e., transaction specificity, from the empirically observable variables, *n*, *k* and *h*.

Hierarchical Random Network with Niche

At one extreme, we build a purely hierarchical network that connects the randomly-arranged *n* firms. The network is constrained to have the same *k* as a random non-hierarchical network, or a given empirical network. Particularly, our hierarchical random network combines a market niche mechanism with a hierarchy mechanism.

We begin by creating an upstream/downstream relationship between firms in the network. To do this, we 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, we define the firm's niche range, r_i, as the interval containing the firm's customers:

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

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 6). Although randomly generated, the network displays strict hierarchy. There are no cycles.

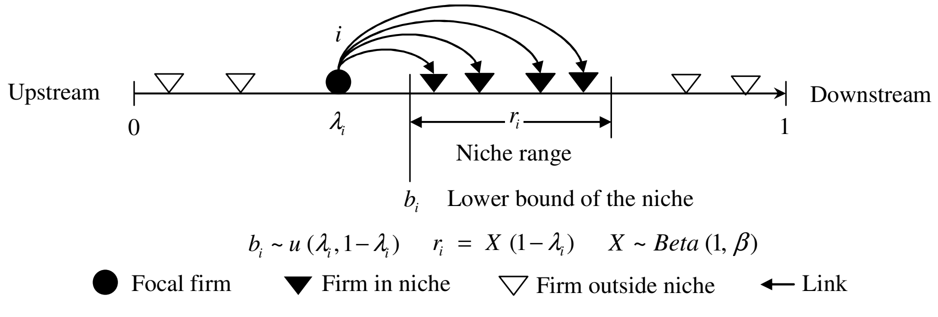


Figure 6 The hierarchical random network configuration

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:

$$E(k_i) = nE\,(r_i) \tag{2}$$

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

$$E(m) = \sum_{i=1}^{n-1} E\,(k_i) = n\sum_{i=1}^{n-1} E\,(r_i) \tag{3}$$

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

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

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

$$E(X) = \frac{2E(k)}{n-1} \tag{5}$$

$E(k)$ is given as an input *k*, the 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 (5). For computational ease, we use a beta-distribution with parameters $(1, \beta)$ 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

$$\beta = \frac{n-1}{2k} - 1 \tag{6}$$

Given the aforementioned array of firms randomly located between zero and one, the simulation generates for each firm a random niche range constrained by Equation (6). The focal firm is then linked to each firm in its niche range.

Properties of the Hierarchical Random Network

The hierarchical random network model suggests several non-trivial statistical properties:

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

(2) Firms close to, but to the left of the rightmost 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 (1) 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 Networks as Mixtures of Hierarchical Random and Pure Random Networks

We 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. The extent of rewiring is determined by a parameter s, which we call "transaction specificity" 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. Intuitively, s represents the degree to which a firm's sales are targeted to a specific group of customers or the degree to which a particular firm fulfills a specific role in the network (sector) (Wasserman and Faust, 1994; White et al, 1976)

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, transactions 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 5.2 later)

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 7 demonstrates a hybrid configuration after rewiring. Cycles and backward links can emerge in the hybrid network.

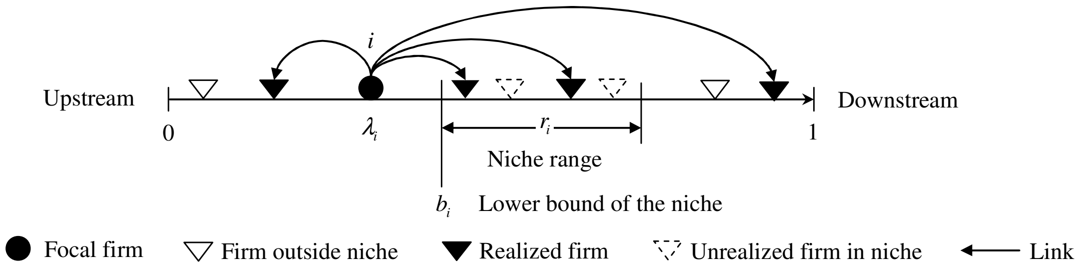


Figure 7. The mixture configuration after rewiring

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, we name it "*Adaptive Niche Model*" as it allows freedom for adaptive transactional relationships deviating from pure hierarchy and niche rules.

Using randomly-generated network models with tunable parameters, we can look at the properties 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 certain structural rules established by n, k, and s and their relationships. And, by tuning the transaction specificity parameter s, we will be able to explore a wide spectrum of industrial systems and their architectures, in order to understand how market size, transaction breadth, and transaction specificity may give rise to different hierarchical architectures.

5.2 Simulation Results

Because the *Adaptive Niche Model* is analytically intractable, we choose to analyze the model by simulations. For each given combination of inputs (*n*, *k* and *s*), we 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.

Impact of Network Size (*n*)

Figure 8 shows the influence of network size (*n*) on average hierarchy degree (*h*) at various combinations of *k* and *s*. As introduced in section 2.3, *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*. 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 $n=100$.

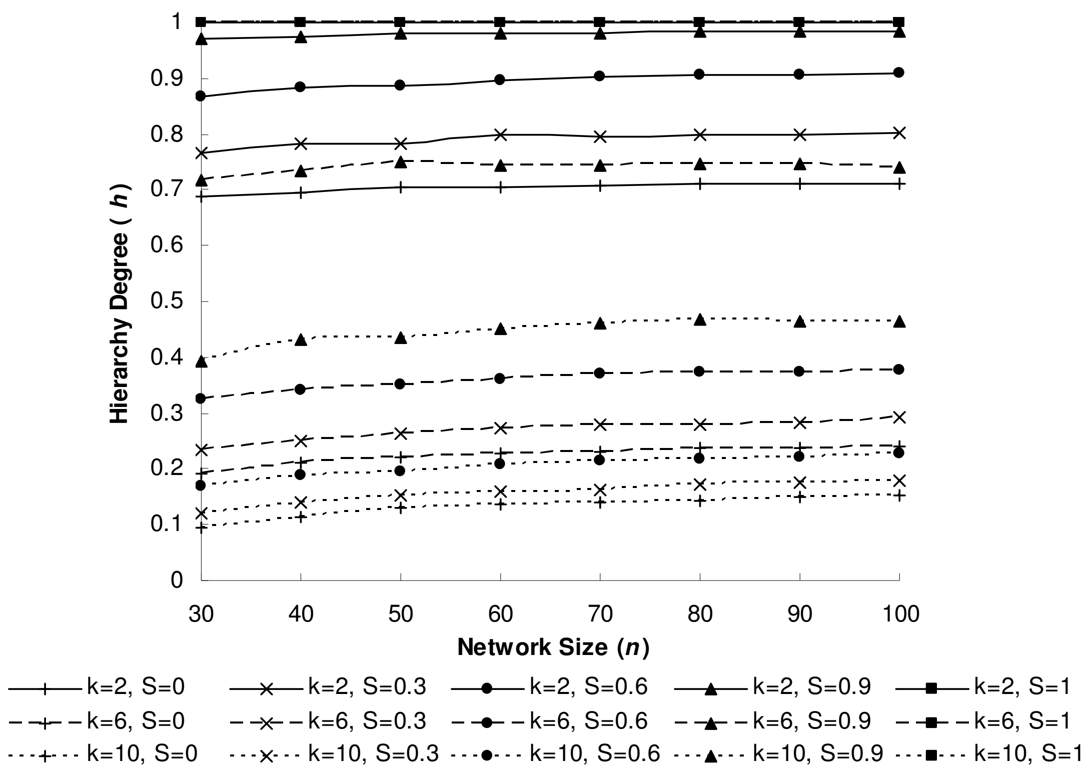


Figure 8 Impact of network size on hierarchy degree

Impact of Transaction Breadth (*k*)

Figure 9 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.

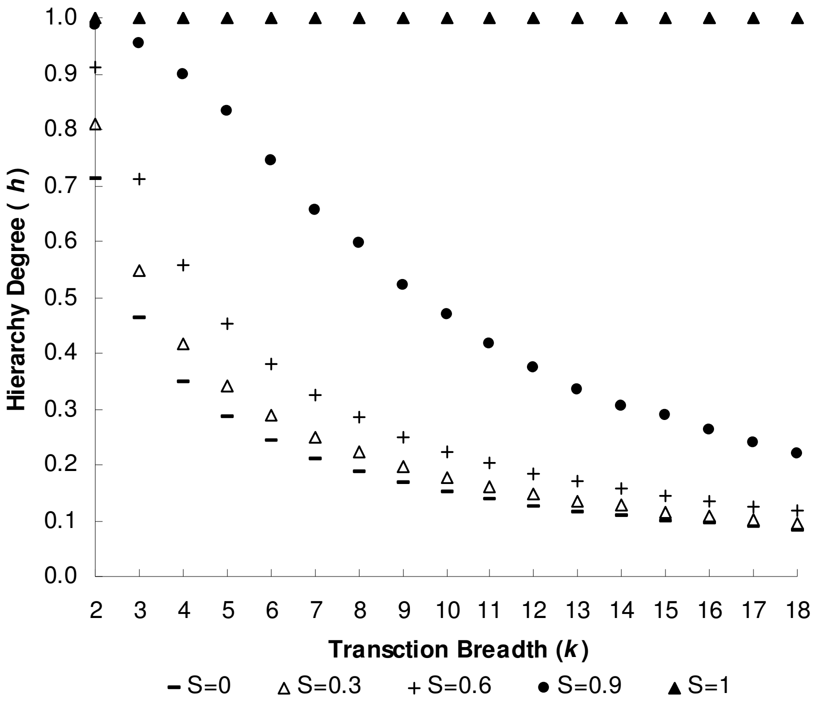


Figure 9 Impact of transaction breadth on hierarchy degree

Impact of Transaction Specificity (*s*)

Figure 10 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*.

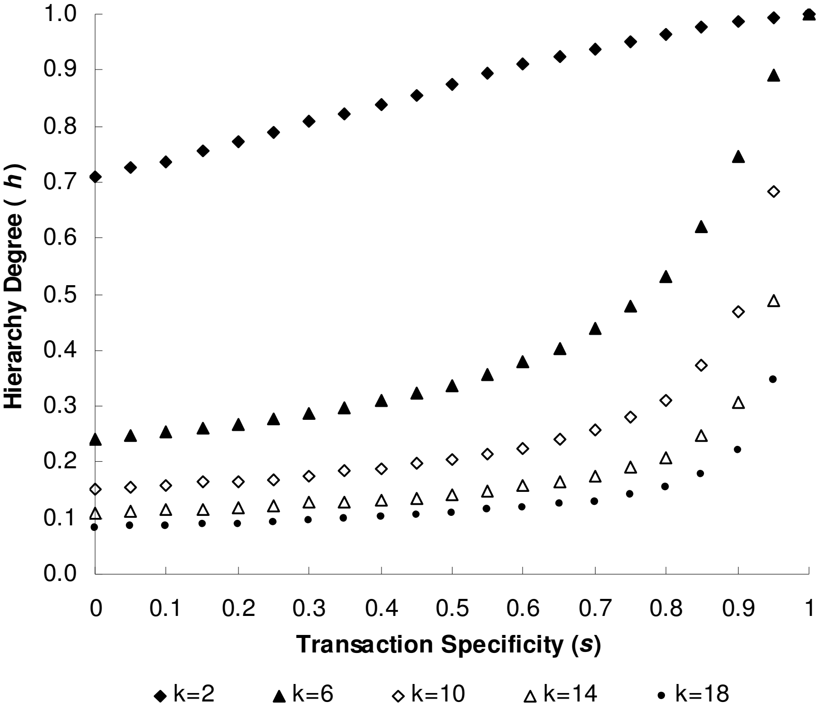


Figure 10 Influence of transaction specificity on hierarchy degree

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*). 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. It follows that, in the context of this model of three 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 1 within the simulation results in Figures 9 and 10, we 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 almost 20 years.

To test the results from the theoretical analysis, we conducted interviews with 3 automotive suppliers and 5 electronics firms in Japan in 2009, with a focus on the firms' design and management of transaction relationships and the related context and decision rationales. The interview data qualitatively demonstrate the same difference in transaction patterns in the two sectors. We will discuss some of the interview findings in further detail in the next section.

Therefore, with the hierarchy metric and the *Adaptive Niche Model* including the design of the tuning parameter -- transaction specificity, we have advanced our probing tool for understanding industry architectures, and gained new insights from the comparative empirical cases. In the next section, we will further discuss and explore the technological and microeconomic mechanisms that may underlie the observable difference in the hierarchical architecture, as well as the inferred difference in transaction specificity, of the two sectors.

6 Technological Influences on Industry Architecture

In the previous sections, we observed higher hierarchy degree, indicating higher transaction specificity, in the automotive sector than in the electronics sector. Such differences in industry architecture and inter-firm transaction patterns may result from differences in the fundamental technological regimes (Nelson and Winter, 1982; Malerba and Orsenigo, 1993; 1996; 1997; Malerba, 2002) of the industrial sectors.

Technological regime defines a technological environment, i.e., the framework conditions in which firms' innovation, learning, and production activities take place, and sectors differ greatly in terms of their technological regimes (Nelson and Winter, 1982; Dosi, 1988; Malerba and Orsenigo, 1996; Malerba, 2002; Castellacci, 2007). Studies on the nature and impacts of technological regimes have shed light on how the characteristics of technological regimes shape the incentives and constraints, and affect the basic behaviors and performances of economic agents in different sectors (Malerba and Orsenigo, 1993; 1996; 1997; Castellac, 2007). In principle, the characteristics of technological regimes may also influence sectoral architectures, as a collective result of the behaviors of individual firms.

While our two subject sectors are similar in many business and economic ways, they differ substantially in the constraints imposed on them by the basic ways their products deliver their respective functions. Technologies that underlie the designs of specific products in production sectors 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). In our two sectors, electronics products mainly store, transform, and transport information, while automobiles mainly store fuel (matter), transform energy (from physical-chemical energy to kinetic energy), transport energy (from engine to wheels), in order to transport human and goods (matter).

In the following we explore the influences that these fundamental differences in technologies may exert as a possible, partial explanation of the differences in industry architecture we observed and modeled above, by analyzing the technical properties of the products and our interview data in the two sectors.

Automotive Sector

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), such substitution has physical limits because an automobile is basically demanded by customers for motion. High power is the basis for automobile's behavior and the main expression of its basic functions.

In the high power system setting, the functional parts of an automobile are powerfully connected. High power also creates difficult-to-anticipate side effects, such as heat and vibration (Whitney, 1996). Meanwhile, a number of systemic requirements, including energy efficiency, emissions, noise, vibration, safety, stability, driving feel, design, cost, etc, need to be met in order to attract consumers, and they 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 of, 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 designed again each time a new vehicle is designed, and are tested and produced for only that vehicle.

This component specificity, which Schilling (2000) called “synergistic specificity”, may give rise to asset specificity (Williamson, 1975; 1981) between buyers and suppliers. 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”. Both sides 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.

This pattern of a well-defined set of similar customers was confirmed in our interviews with three major automotive suppliers, including one material supplier and two component suppliers. 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 joint products and processes (Sako, 1992; Helper, MacDuffie and Sabel, 2000). Such relationships generally take a long time to build and may give rise to organizational rigidities (Kaplan and Henderson, 2005). We found the interviewed firms' are either unwilling to diversify their product portfolios, or incapable of creating new products for customers outside their main niches[5]. As our model shows, when the pattern of high transaction specificity is aggregated to the sector as a whole, it gives rise to hierarchy – that is, a one directional flow of goods in the sector as a whole.

Electronics Sector

In electronics products (e.g. computers, communications, and 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, use limited size and weight for products, and can be accomplished at very low power levels. The interactions among different functional parts of an electronics product are relatively weak. Lower power brings in less severe and less frequent difficult-to-anticipate side effects, so the integration of them is relatively easy. Such cases are often regarded as "modular" (Baldwin and Clark, 2000). Clearly there are gradations of modularity because there are degrees of connection.

At one extreme of modularity, codified behaviors and standardized interfaces are pursued economically and reliably. With standardized interfaces, the behavior of components does not

---

[5] In one interviewed company, we found the firm is unwilling to diversify their products and transactional relationships because of its failed experience of diversification. This is a major automotive electrical and electronic system supplier. In the 1990s, the supplier tried to utilize its know-how on electronics to enter the consumer electronics markets (e.g. LCD, TV). The expansion was unprofitable largely because of the unfamiliarity of marketing and distribution channels. Later it turned back to concentrate on automobiles. The interviewee told us "the company's DNA is automotive". In another automotive electronics supplier we interviewed, the dedication to tailored automotive needs have constrained its capability to develop competitive not-for-automotive products. The interviewee from this company told us that their product development team has been accustomed to the integral designs and slow pace of automotive business, which make them incapable to develop competitive components in

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, e.g. memory chip, battery, can be conducted without detailed knowledge of the products in which they are used (Whitney, 1996). Even though some electronics components are also customized to some extent in some situations, e.g. novel product development (Yasumoto and Shiu, 2008), in the low-power setting they are still believed to be more "modular" than those energy-processing mechanical components in automobiles, such as the parts of engine and transmission[6]. Thus, the extra coordination and customization efforts may not increase asset specificity to the level required in integrating automotive components.

The modular nature of low-power electronics has several further implications to transaction patterns. First, modular interfaces are the thin crossing points (Puranam and Jacobides, 2006; Baldwin, 2008) where transaction costs (Coase, 1937) are low, and result in low asset specificity between suppliers and customers (Williamson, 1975; 1981; Baldwin, 2008). This in turn makes arm-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.

Second, the modularity of electronics allows independent, unsynchronized (vs. interdependent and simultaneous) development activities, which in turn leads to high rates of modular product innovations (Baldwin and Clark, 2000) and short product cycles[7]. Koh and Magee (2008)

---

the dynamic consumer electronics sector.

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

[7] Three major electronics manufactures that we interviewed identify "short product cycle" as their major challenge.

showed that information technologies achieved much higher performance progress rates than energy technologies in the past 100 years. This also creates volatile demands—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 in nature have larger production scale and higher product development speed than the less efficient internal component divisions of large vertically-integrated electronics firms, particularly for such standardized components as semiconductors. Thus, as indicated in our interviews with the major electronics companies in Japan, the previously-integrated electronics firms are largely procuring components from external suppliers which can offer better performance, price, and quality than internal production[8]. Meanwhile, the internal component divisions of big electronics companies strive to sell components to the industrial market in order for more effective use of resources and capacities, and benchmarking to improve efficiency. When a company (1) partially "uses" components from internal divisions while simultaneously partially "procures" components from external companies, and (2) its component divisions partially "provide" in-house needs meanwhile partially "sell" to other companies, it is in an intermediate status between complete vertical integration and disintegration, where firms' vertical boundaries are "permeable" (Jacobides and Billinger, 2006)[9]. When a company both buys components from and sells components to the industrial market via its vertical boundary, i.e. fulfills multiple roles,

---

This was not found in the interviews with automotive suppliers. Short product cycle drives up the competition on both new technology and cost simultaneously, and many of the firms' make-or-buy strategies are responses to it.

[8] 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.

transaction specificity may be reduced to the extent that cycles will likely emerge around this company[10].

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 Sidney, 1994). On the other hand, it also means that a firm making particular components can have a wide range of customers making very different products. 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 “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 also sustains the dynamics of architectural innovations (Henderson and Clark, 1990) and the motivation of the diversified electronics companies to pursue architectural innovations. In history, the Japanese electronics industry has grown upon their success in adapting existing fundamental electronic and electrical technologies to develop successful system applications, such as radio, walkman, etc. (Nakayama, et al, 1999). A manager

---

[9] Past researches on firm boundaries (empirical studies in particular) have largely focused on either make or buy as a dichotomous choice, or concurrent sourcing, i.e. both make and buy (Parmigiani, 2007), with the neglect of “provide” and “sell” transactions which may also concurrently happen.

[10] Theoretically, if all the procurements of companies are only for further integrations into larger products (excluding tooling, office uses), any supply cycle necessarily needs to include at least one member with permeable vertical boundary.

we interviewed used such a motivation to partially explain why the Japanese firms prefer the integrative organization choice of vertically "permeable" boundary and horizontal diversification (of system products) versus complete disintegration (e.g. HP) and horizontal specialization (e.g. Nokia) -- the diverse component-level technologies, capabilities, and resources of different divisions may be potentially remixed and recombined across the divisional boundaries to create new system products when found valuable[11].

In summary, we have argued that industry architectures are in part influenced by the technological nature of products through a chain of logic, which correlates technologies to product architectures, innovation dynamics, firm behaviors, transaction patterns and industry architecture. On the one hand, the high power nature of an automobile promotes mutual specificity in its components, production assets, and transactional relationships, and hand-in-glove contracts. And high levels of transaction specificity across a sector give rise to a hierarchical industry architecture. 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 scale and cost. In such an environment, firms not only diversify their product lines, but also make their vertical boundaries "permeable" in order for more effective use of resources and capacities, linking complementary capabilities, and benchmarking to improve efficiency. Then all these lead to low levels of transaction specificity across a sector, which further give rise to non-hierarchical and multidirectional industry architecture.

---

[11] This is a partial motivation. First, firms diversify partially in order to tackle the dynamic and compound demands. Second, another firm that we interviewed prefers vertically-permeable boundary against complete disintegration also

In the analysis of this section, high and low levels of transaction specificity can be logically traced back to differences in the power level of underlying product technologies. In our causal model, high and low levels of transaction specificity lead to high and low levels of hierarchy in the resulting network 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.

In a nutshell, we argue that 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. This hypothesis was based on our exploratory analysis of two sectors, which differ in their technological regimes but are in the same historical, culture and macroeconomic context of Japan. It can be taken to other technologies and sectors to see if it holds up to further empirical tests.

7 Conclusions

This paper has explored how industries are organized at the sector level in an attempt to reveal the underlying rules that determine how industry architectures form and change. We first introduced a network-based metric and method to measure the degree of hierarchy of an industry sector, and then applied them to compare two large industrial sectors in Japan: automotive and electronics. Our empirical analysis shows that the automotive sector exhibits a significantly higher degree of hierarchy than the electronics sector. Then, we used a mixed strategy to explain

---

because the component divisions remain profitable, by benchmarking with the peers via permeable boundary.

this observed difference in hierarchy.

At the first step of explanation, we built a network model, i.e. "*Adaptive Niche Model*", to connect the macro pattern, i.e., hierarchy, to local or micro patterns of connection at the level of individual firms, e.g. transaction breadth or how many connections are executed, and transaction specificity or where the connections are oriented. By interpolating the empirical results within the simulation results, we infer transaction specificity, which is significantly higher in the automotive sector than in the electronics sector. Then, based on a micro analysis of the nature of products and our interview data in the two sectors, we propose that the higher hierarchy degree and transaction specificity in the automotive sector compared to the electronics sector may result from the high-power nature of energy and matter processing of the components in an automobile, and the low-power nature of information processing of the electronic components in electronics products.

This research hopefully points the way to new approaches for understanding industry architectures and the factors that influence the architecture of industry sectors. To advance further, a number of hurdles must be overcome. Primary among these is the difficulty of obtaining quality data. We only have the data for two sectors. Our hypothesis could be better tested if data for more and diverse sectors are collected. It is usually difficult to collect and compile industry-wide data not only because of the 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 bias. The empirical measurement bears the risk of the deficits in the data.

Second, the hierarchy degree may change as the eco-system evolves (Simon, 1962; Luo and Magee, 2009). This may contribute to some extent to the difference in hierarchy degree if the two sectors are at different stages of their industry life cycles. Our multi-year data shows the automotive sector has remained highly hierarchical in two decades, but we do not have multi-year data to detect the evolving pattern of the electronics sector. So we relied on literature and our interviews done in 2009 to show that, cycles are still, if not more, widely existing in the electronics sector, and keep hierarchy constantly low. However, the electronics sector may become more hierarchical as it matures, and the hierarchy degree of the automotive sector may decrease temporarily if a new technological paradigm (e.g. affordable electric vehicle) emerges and disrupts the current dominant one. Thus we hope readers will view our conjecture on the influence of technology on industry architectures as a call for awareness and future research, rather than a claim that this is the only mechanism that affects industry architectures.

In fact, while automobiles and electronics operate under different technological constraints, these constraints are summarized here in terms of the amount of power involved in their functions. This is also an aggregate characterization which 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. It is limited in not indicating additional mechanisms that lead to asset and transaction specificity beyond the high power and low power technologies considered here.

Third, we lack sufficient means for visually representing these large and complex networks. This is a known problem in network theory, and we have 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 quantitative aggregate metrics.

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. Numerous ways to relieve this simplification are available, and using them will add nuance to the model, probably by differentiating suppliers that play different roles at the system, subsystem, or discrete component levels of the network.

These limitations may be looked at as an invitation to explore these connections further in order to gain more understanding into both the common and different forces that act to create the architectures of industry sectors.

Acknowledgments

We thank Joel Moses and Daniel Roos for initial discussions and support that motivated this research. The authors also thank the International Motor Vehicle Program and the MIT-Portugal

Program at MIT for financial supports. We particularly thank Takahiro Fujimoto, Daniel Heller, Masanori Yasumoto, and other researchers at the Manufacturing Management Research Center at the University of Tokyo for generous support and help with the field work and data collection in Japan. Finally, the authors thank the executives and managers of the investigated firms for their time, patience, valuable inputs, and the spirit of knowledge sharing that have allowed a deep understanding on their strategies and the related context and rationales. The authors alone are responsible for any errors and oversights.

References

Abernathy, W. J., K. B. Clark and A. M. Kantrow (1983), *Industrial Renaissance: Producing a Competitive Future for America*. Basic Books: New York.

Ahl, V. and T. F. H. Allen (1996), *Hierarchy Theory: A Vision, Vocabulary and Epistemology*. Columbia University Press.

Baker, G., Gibbons R. and K. J. Murphy (2002), ‘Relational contracts and the theory of the firm,’ *The Quarterly Journal of Economics*, **117**, 39-84.

Baldwin, C. Y. and K. B. Clark (2000), *Design Rules, Volume 1: The Power of Modularity*. MIT Press: Cambridge, MA.

Baldwin, C. Y. (2008), ‘Where do transactions come from? modularity, transactions, and the boundaries of firms,’ *Industrial and Corporate Change*, **17**(1), 155-195.

Burt, R. and I. Talmud (1993), ‘Market niche,’ *Social Networks*, **15**, 133-149.

Castellacci, F. (2007), ‘Technological regimes and sectoral differences in productivity growth,’ *Industrial and Corporate Change*, **16**(6), 1105–1145

Chandler, A. D. Jr (1962), *Strategy and Structure*. MIT Press: Cambridge, MA.

Christensen, C. M. and R. S. Rosenbloom (1995), ‘Explaining the attacker's advantage: technological paradigms, organizational dynamics, and the value network,’ *Research Policy*, **24**, 233-257

Clauset, A., C. Moore and M. E. J. Newman (2008), ‘Hierarchical structure and the prediction of missing links in networks,’ *Nature*, **453**, 98–101.

Coase, R. H. (1937), ‘The nature of the firm,’ *Economica*, **4**(4), 386-405.

Dalziel, M. (2007), ‘A systems-based approach to industry classification,’ *Research Policy*, **36**, 1559-1574.

Davis, R. and I. M. Duhaime (1992), ‘Diversification, vertical integration, and industry analysis: new perspectives and measurement,’ *Strategic Management Journal*, **13**(7), 511-524.

Dodwell Marketing Consultants (1993), *The Structure of Japanese Auto Part Industry*. Japan.

Dodwell Marketing Consultants (1993), *The Structure of Japanese Electronics Industry*. Japan.

Dosi, G. (1988), ‘Sources, procedures, and microeconomic effects of innovation,’ *Journal of Economic Literature*, **26**(3), 1120-1171

Fujimoto, T. (2007), ‘Architecture-based comparative advantage -- a design information view of manufacturing,’ *Evolutionary and Institutional Economics Review*, **4**, 55-112.

Helper, S, MacDuffie, J. P. and C. Sabel (2000), ‘Pragmatic collaborations: advancing knowledge while controlling opportunism,’ *Industrial and Corporate Change*, **9**(3), 443 - 488.

Henderson, R. M. and K. B. Clark (1990), ‘Architectural innovation: the reconfiguration of existing product technologies and failure of established firms,’ *Administrative Science*

Quarterly, **35**, 9-30

Hubka, V. and E. E. Eder (1988), *Theory of Technical System*. Springer–Verlag: Berlin.

Jacobides, M. G. (2005), 'Industry change through vertical disintegration: how and why markets emerged in mortgage banking,' *Academy of Management Journal*, **48**(3), 465-498.

Jacobides, M. G. (2006), 'The architecture and design of organizational capabilities,' *Industrial and Corporate Change*, **15**(1), 151-171.

Jacobides, M. G. and S. Billinger (2006), 'Designing the boundaries of the firm: from "make, buy, or ally" to the dynamic benefits of vertical architecture,' *Organization Science*, **17**(2), 249-261.

Jacobides, M. G., Knudsen, T. and M. Augier (2006), 'Benefiting from innovation: value creation, value appropriation and the role of industry architectures,' *Research Policy*, **35**, 1200-1221.

Jacobides, M.G. and S.G. Winter (2005), 'The co-evolution of capability and transaction costs: explaining the institutional structure of production", *Strategic Management Journal*, **(26)**5, 395-413.

Kaplan, S. and R. Henderson (2005), 'Inertia & incentives: bridging organizational economics & organizational theory,' *Organization Science*, **16**(5), 509-521.

Kauffman, S. A. (1993), *The Origins of Order: Self-organization and Selection in Evolution*. Oxford University Press: New York.

Koh, H., Magee, C. L. (2006), 'A functional approach for studying technological progress: application to information technology,' *Technological Forecasting & Social Change*, **73**, 1061-1083.

Koh, H., Magee, C. L. (2008), 'A functional approach for studying technological progress:

extension to energy technology,' *Technological Forecasting & Social Change*, **75**, 735-758.

Langlois, R. N. and P. L. Robertson (1992), 'Networks and innovation in a modular system: lessons from the microcomputer and stereo component industries,' *Research Policy*, **21**, 297-313.

Luo, J. and C. Magee (2009), 'Detecting evolving patterns of self-organizing networks by flow hierarchy measurement,' *Submitted Manuscript*, Massachusetts Institute of Technology.

Malerba, F. (2002), 'Sectoral systems of innovation and production,' *Research Policy*, **31**, 247-264.

Malerba, F. and L. Orsenigo (1993), 'Technological regimes and firm behavior,' *Industrial and Corporate Change*, **2**(1), 45-71.

Malerba, F. and L. Orsenigo (1996), 'Schumpeterian patterns of innovation are technology-specific,' *Research Policy*, **25,** 451–478.

Malerba, F. and L. Orsenigo (1997), 'Technological regimes and sectoral patterns of innovative activities,' *Industrial and Corporate Change*, **6**(1), 83-118.

MacDuffie, J. P. (2006), 'Modularity and the automobile: What happened when the concept hit the road,' *International Motor Vehicle Program Automotive Mini Conference*, Cambridge, MA, USA, June 6, 2006.

Magee, C. L. and O. de Weck (2004), 'Complex system classification,' *Fourteenth Annual International Symposium of the International Council on Systems Engineering (INCOSE)*, 1-18.

Moses, J. (2002), 'The anatomy of large scale systems,' Working Paper, ESD-WP-2003-01.25, Engineering Systems Division, MIT.

Moses, J. (2004), 'Three design methodologies, their associated organizational structures and their relationship to various fields,' *MIT Engineering Systems Symposium*, Cambridge, MA, USA, March 29-31. Available at: http://esd.mit.edu/symposium/pdfs/papers/moses.pdf, accessed on November 10, 2009.

Murmann, J. P. and K. Frenken (2006), 'Toward a systematic framework for research on dominant designs, technological innovations, and industrial change,' *Research Policy*, **35**, 925-952.

Nagaoka, S., Takeishi, A. and Y. Norob (2008), 'Determinants of firm boundaries: empirical analysis of the Japanese auto industry from 1984 to 2002,' *Journal of the Japanese and International Economies*. **22**(2), 187-206.

Nakayama, W., Boulton, W. and M. Pecht (1999), '*The Japanese electronics industry*,' Boca Raton, Fla.: Chapman & Hall/CRC Press.

Nelson, R. and S. Winter (1982), '*An evolutionary theory of economic change*,' The Belknap Press of Harvard University Press: Cambridge, MA.

Newman, M. E. J. (2003), 'The structure and function of complex networks,' *SIAM Review,* **45**, 167-256

Nobeoka, K. (1996), 'Alternative component sourcing strategies within the manufacturer-supplier network: benefits of quasi-market strategy in the Japanese automobile industry,' *Kobe Economic & Business Review*, **41**, 69-99

Paprzycki, R. (2005), *Interfirm networks in the Japanese electronics industry*. RoutledgeCurzon: London and New York.

Parmigiani, A. (2007), 'Why do firms both make and buy? an investigation of concurrent sourcing,' *Strategic Management Journal*, **28**, 285–311

Penrose, E. (1959), *The Theory of the Growth of the Firm*. Basil Blackwell: Oxford.

Podolny, J., Stuart, T. E. and M. Hannan (1996), 'Networks, knowledge, and niches: competition in the worldwide semiconductor industry, 1984-1991,' *American Journal of Sociology*, **102** (3), 659-689.

Puranam, P. and M. G. Jacobides (2006), 'The dynamics of coordination regimes: implications for organization design,' Working Paper, London Business School, May.

Rivkin J. W. and N. Siggelkow (2002), 'Organizational sticking points on NK landscapes,' *Complexity*, **7**(5), 31-43.

Sako, M. (1992), *Prices, quality, and trust: inter-firm relations in Britain and Japan*, Cambridge University Press: Cambridge, UK.

Schilling, M. A. (2000), 'Towards a general modular systems theory and its application to interfirm product modularity,' *Academy of Management Review,* **25**, 312-334.

Simon, H. A. (1962), 'The architecture of complexity,' *Proceedings of the American Philosophical Society*, **106**, 467-82.

Sturgeon, T. J. (2002), 'Modular production networks: a new American model of industrial organization,' *Industrial and Corporate Change*, **11**(3), 451-496.

Teece, D. J. (1982), 'Towards an economic theory of the multiproduct firm,' *Journal of Economic Behavior and Organization*, **3**, 39-63.

Teece, D. J., Rumelt, R., Dosi, G. and S. Winter (1994), 'Understand corporate coherence: theory and evidence,' *Journal of Economic Behavior and Organization*, **23**, 1-30

Tushman, M. L. and J. P. Murmann (1998), 'Dominant designs, technology cycles and organizational outcomes,' *Research in Organizational Behavior*, **20**, 231-266

van Wyk, R. J. (1988), 'A standard framework for product protocols,' in T. Khalil (ed), *Management of Technology*, Geneva, 93-99.

Wasserman, S. and K. Faust (1994), *Social Network Analysis: Methods and Applications.* Cambridge University Press: Cambridge; New York.

Watts, D. J. and S. H. Strogatz (1998), 'Collective dynamics of 'small-world' networks,' *Nature*, **393**, 440-442.

Williamson, O. E (1975), *Markets and Hierarchy*. Free Press: New York

Williamson, O. E. (1981), 'The economies of organization: the transaction cost approach,' *American Journal of Sociology*, **87**, 548-577.

Williamson, O. E. (1985), *The Economic Institutions of Capitalism*. Free Press: New York.

Wilson, D. (1969), 'Forms of hierarchy: a selected bibliography,' In L. L. Whyte, A. G. Wilson and D. Wilson (eds.), *Hierarchical Structures*, American Elsevier: New York, 287-314.

White, H., Boorman, S. A. and R. L. Breiger (1976), 'Social structure from multiple networks: Part I. block models of roles and positions,' *American Journal of Sociology*, **81**, 730-780.

Whitney, D. E. (1996), 'Why mechanical design cannot be like VLSI design,' *Research in Engineering Design*, **8**(3), 125-138.

Woodard, C. J. (2006), *Architectural strategy and design evolution in complex engineered systems*, Doctoral Dissertation, Harvard University, Cambridge, MA.

Yasumoto, M. and Shiu, J. M. (2008), 'Why is interfirm collaboration called for in novel technology platform adoption?: cases from the Japanese, Taiwanese, and Chinese mobile phone industries', *Discussion Paper Series*, #2008-MMRC-225, Manufacturing Management Research Center (MMRC), University of Tokyo.