Understanding Complex Product and Service Delivery Systems

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This chapter considers alternative views of complex systems that deliver products and services to consumers and other constituencies. Holistic views of complex systems are discussed in the context of several public-private systems and a notional model is introduced that relates complexity to the number of enterprises in a domain and the levels of integration required for these enterprises to function successfully. Reductionist views of complexity are discussed, including the basic premises underlying axiomatic models of complexity. An information theoretic model is introduced for calculating the complexity of value delivery networks and applied to assessing the complexity of several enterprise domains. The use and value of models of complex systems are discussed.

INTRODUCTION

This chapter considers complex product and service delivery systems. Some of these systems are focused on product delivery. A good example is systems that design, develop, manufacture, and sustain aircrafts and automobiles. These systems are laced with services, but the focus is on creating and sustaining the product. In contrast, there are systems that focus on service delivery. Examples include networks that provide healthcare, education, defense, finance, and food (Basole & Rouse, 2008). While there are many products that enable the services in these networks, the focus is on the services provided. Note that none of the examples just discussed are purely product or service delivery systems, although they are often seen and managed that way.

We seek to understand the complexity of these types of systems in order to better design, operate, and maintain them (Rouse, 2003, 2007a). This chapter considers definitions and models of complexity, as well as the application of these models to particular systems. Models based on both holistic and reductionist views of these systems are considered. We argue that the reductionist approach provides important insights but is not sufficient due to emergent properties of complex systems. Hence, a balance between reductionist and holistic approaches is necessary to understand and gain insights into design, operation, and maintenance of these systems.

This chapter proceeds as follows. The next section considers holistic views of complex systems in the context of several public-private systems. A notional model of complexity is introduced that relates complexity to the number of enterprises in a domain and the levels of integration required for these enterprises to function successfully. The following section discusses reductionist views of complexity. The basic premises underlying axiomatic models of complexity are discussed including typical definitions of the structure and state of a system. An information theoretic model is introduced for calculating complexity in terms of the number of bits of information that must be processed to estimate the state of a complex system. This model is applied to assessing the complexity of several enterprise domains. The chapter concludes with a discussion of the use and value of models of complex systems.

HOLISTIC VIEWS

The reductionist approach, discussed later in this chapter, attempts to decompose a system into its structural elements to understand how these elements function together to yield the behavior of the system. In contrast, the holistic approach considers the characteristics and functioning of the overall system with little if any decomposition.

When one compares holistic views of aircraft manufacturing and healthcare delivery, for example, it quickly becomes evident that these are quite different types of systems. Aircraft manufacturing is an example of a complex product delivery system where many things have to come together into one smoothly functioning entity, such as an airplane or automobile. In the case of an airplane, for example, companies collaborate and interact during the design process and form global supply relationships to provide and deliver major components, such as the wing, the fuselage or engine. In this type of domain, the physical products or “goods” are the center of this kind of complex system.

Healthcare delivery, in contrast, is an example of a complex service delivery system where the complexity is due to the many organizational seams that hinder alignment of objectives and incentives, as well as information flow. There are many products that enable the services provided in such systems but, unlike complex product delivery systems, these products are not a primary source of the complexity of such systems. The socio-technical nature of the system is the primary source of complexity (Rouse & Baba, 2006). In other words, people and organizations, rather than technology, are dominant (Rouse, 2007b).

Large-scale public-private systems provide interesting opportunities to elaborate holistic views of complex systems. Such systems involve numerous private enterprises operating in a marketplace that is heavily influenced by government policy and, in some cases, by government funding. Examples include:

- *Defense*: Many interdependent private enterprises with integrated delivery of products and systems for public use, one source of payment, and substantial and integrated public oversight
- *Education*: A large number of independent, mostly public, enterprises with distributed delivery of products and services, many from private enterprises, as well as distributed payment and distributed public oversight
- *Finance*: Many interdependent private enterprises with integrated delivery of shared services, but distributed delivery of products and services to consumers, and distributed payment with integrated public oversight
- *Food*: A large number of independent private enterprises with integrated delivery systems, but distributed products and payment, with integrated public oversight of products, but less so services
- *Healthcare*: A very large number of independent private and public enterprises with distributed delivery of products and services but, for older and poor consumers, one source of payment, and integrated public oversight of products, but less so services

Note that *Defense* is a complex private sector product delivery system, embedded in a complex public sector service delivery system. *Education* and *Healthcare*, in contrast, are primarily complex service delivery systems, with both private and public sector service providers. *Finance* and *Food* predominantly involve private sector product and service delivery, with public sector oversight, albeit quite intense of late for *Finance*.

Table 1 summarizes the holistic characteristics of public-private enterprise discussed above. *Defense* is the most integrated while *Education* is the least integrated of these enterprises. Note that while oversight is integrated for *Finance*, *Food*, and *Healthcare*, the level does not approach that of *Defense*.

	No. of Enterprises	Delivery	Products/ Services	Payment	Oversight
Defense	1,000	Integrated	Integrated	Integrated	Integrated
Education	100,000	Distributed	Distributed	Distributed	Distributed
Finance	10,000	Integrated	Distributed	Distributed	Integrated
Food	100,000	Integrated	Distributed	Distributed	Integrated
Healthcare	1,000,000	Distributed	Distributed	Integrated	Integrated

Table 1. Characteristics of Public-Private Enterprises

In order to assess and contrast the complexity of these five domains, consider the following notional model of complexity *C*.

$$C = f\left(NE, DI, PSI, PI, OI\right) \tag{1}$$

where *NE* is the number of enterprises, *DI* is the level of delivery integration, *PSI* is the level of product/service integration, *PI* is the level of payment integration, and *OI* is the level of oversight integration.

Delivery integration refers to the extent that the flow of resources across the value network is managed as a single or integrated entity. Product/service integration refers to the extent to which the consumer receives a single product/service. Payment integration refers to the extent a single user pays for the products/services received. Oversight integration refers to the level of influence, management, and control of product and service delivery by a third-party constituent.

Note that integrated information systems are key to the other types of integration, particularly *DI* and *PI*. This is also the case for *PSI* when the product or service involves access to and use of information, such as in online financial services. The level of information integration differs substantially across types of enterprise. *Finance* has the highest level of information integration; *Healthcare* the lowest. The consequence is the well-known enormous paperwork burden experienced by *Healthcare*.

We would expect *C* to increase with *NE* and levels of integration – *DI, PSI, PI*, and *OI* – either required for success or imposed by oversight. *Education* is the least integrated enterprise and, hence, the least complex despite the large number of independent enterprises. It seems reasonable to argue that *Finance* is less complex than *Food* as it is a much less diverse industry and, until recently, oversight was less complicated; a case in point is the contrast of the Federal Reserve with the Food and Drug Administration.

Considering *Healthcare*, the fragmentation of provider enterprises and the third-party payment system, via either employers or government, contributes substantially to the complexity of this enterprise (Rouse, 2008). The lack of standard processes and practices can be contrasted with *Food* or, in general, *Retail* (Basole & Rouse, 2008). Hence, the complexity of *Healthcare* exceeds that of *Food*.

It could be argued that *Defense* has the greatest complexity due to the levels of integration imposed across all aspects of the enterprise. However, relatively few enterprises are involved and standard processes and practices are dictated by the single customer. Consequently, it can be argued that *Health* exceeds *Defense* in complexity.

Relationship (2) summarizes this notional analysis of the complexity of these public-private enterprises.

$$C_{Healthcare} > C_{Defense} > C_{Food} > C_{Finance} > C_{Education} \tag{2}$$

Later in this chapter, we discuss a model that enables going beyond the ordinal relationship in (2) and quantifying complexity.

To probe a level deeper into holistic views of complexity, consider the differences between enterprises that produce airplanes and automobiles, and enterprises that deliver healthcare. Also, consider how the complexity of these enterprises differs depending on their relationship with the government. Table 2 summarizes these contrasts.

	Government	Non-Government
Airplanes & Automobiles	2nd in complexity due to processes imposed by government	3rd in complexity due to number of things that must function together
Healthcare Delivery	4th in complexity due to single organization provider and payer	1st in complexity due to many organizational seams

Table 2. Contrasts of Complexity

Healthcare delivery in the private sector is the most complex due to the many organizational seams that hinder alignment of objectives and incentives, as well as information flow. In contrast, healthcare delivery in the government via the Military Health System and Veterans Administration is the least complex because a single organization provides and pays for the care. Clearly, the nature of the enterprise, such as characterized in Table 1, has an enormous impact on these two enterprises providing the same products and services.

Enterprises that provide custom-designed airplanes, automobiles, and other systems to the government are the second most complex because of the processes and practices imposed by the government (Pennock, Rouse, & Kollar, 2007). Enterprises that provide the same types of systems to non-government customers are less complex because their processes and practices are designed to minimize overhead rather than maximize scrutiny. In this case, the product or system is evaluated or rated, but not the process that created it.

In summary, holistic views of complex systems can enable qualitative analyses that provide insights into sources of complexity. Such analyses are particularly useful when they enable benchmarking one type of systems versus another. We can see from the foregoing why the complexity of various public-private systems differs.

REDUCTIONIST VIEWS

Reductionist approaches to modeling involve decomposing a system into its elements, determining the relationships among these elements, and composing these relationships into an overall model of the system. In this section, we apply this approach to developing an axiomatic model of the complexity of a system using network models and information theory.

Basic Premises

It is important to begin by discussing a few basic premises. First, and perhaps foremost, complexity is not a property of a system independent of its context. More specifically, complexity is related to the intentions (or objectives) and expertise of the observer relative to the system of interest (Rouse, 2007a). Thus, for example, a large aircraft that is used as a paperweight is not complex; it is simply a large mass. If, on the other hand, one's intention or objective was to operate and maintain this aircraft, it could be quite complex.

Elsewhere we have argued that complexity is the amount of information that must be processed to achieve the objectives of interest, expressed in bits or bits/second (Basole & Rouse, 2008). Observers' objectives and requisite expertise can differ for the same system, for example:

- Design and develop an airplane or automobile
- Manufacture and assemble an airplane or automobile
- Drive or fly an airplane or automobile
- Maintain an airplane or automobile
- Ride in an airplane or automobile

Thus, riding in an airplane or automobile is not very complex, but designing and developing these vehicles is likely to be quite complex, especially if one has little expertise in performing these design and development tasks.

A generalized objective with respect to a complex system is to determine its state, perhaps in order to influence or control the system. While achieving this objective is premised on the system being observable and controllable, consideration of these constructs is beyond the scope of this chapter (Sage & Rouse, 2009). Consequently, we define complexity as the amount of information that must be processed to determine the state of a complex system, expressed in bits (or binary units) (Basole & Rouse, 2008).

Models of Complex Systems

In order to operationalize this definition, a model of the system of interest is needed. An enterprise system can be modeled as a highly interconnected and layered network of physical, economic, informational, and social relationships. It is rooted in the idea that many natural, social and economic phenomena are in fact complex networked systems (Arthur, 1999). In the sciences, for example, biologists have examined networks of interactions between genes and proteins to study the behavior of organisms, to model diseases, or to explore the dynamics of food webs (Cohen, Briand, & Newman, 1990; Kauffman, 1969; Newman, 2003). Engineers and computer scientists have studied information and technological networks, such as the electric power grid, telecommunications networks, and the Internet (Broder, et al., 2000; Newman, 2003; Strogatz, 2001). Networks have also been studied in the social sciences. Sociologists, for example, have examined the connections among people to understand the functioning of human society (Wasserman & Faust, 1994). Economists have investigated how innovations diffuse through a network of individuals and organizations.

Along the same lines, the conceptualization of product and service delivery systems as complex networks is not new. It is based on the fundamental thinking that individuals and organizations do not merely operate in dyadic relationships, but are deeply embedded in complex economic and social systems consisting of numerous inter- and intra-organizational relationships. This perspective replaces the traditional view of value chains proposed by Porter which suggested a linear value flow from raw material suppliers to manufacturers to consumers (Normann & Ramirez, 1993; Porter, 1985).

Today, however, value is provided by a myriad of multidirectional relationships across and between businesses and consumers. As a result, products and services are designed, created, delivered, and provided to customers via complex processes, exchanges, and relationships (Chesbrough & Spohrer, 2006; Fitzsimmons & Fitzsimmons, 2001; Vargo & Lusch, 2004) This has led traditional value chains to evolve to value networks (Allee, 2000; Bovet & Martha, 2000; Kothandaraman & Wilson, 2001; Parolini, 1999), which are characterized by a complex set of direct and indirect ties between various participants, or actors, all delivering value either to their immediate customer or the end consumer . The value network construct thus assumes the organization to be part of a larger complex networked system of organizations, or extended enterprises, that together create (i.e., co-create) value. (Allee, 2000; Basole & Rouse, 2008; Brandenburger & Nalebuff, 1997; Dyer, 2000; Stabell & Fjeldstad, 1998).

Complex systems in a broad range of domains tend to exhibit some common characteristics. Generally speaking, complex systems consist of a large number of interacting entities, e.g., components or agents (Arthur, 1999). Each entity's behavior is commonly governed by a set of rules, which may range from physical principles to economic or social rules. The relationships among these entities and their consequent interactions can often lead to complex "emergent" structures and dynamic behaviors.

Modeling a complex system, such as a product or service delivery system, requires specification of the entities and relationships that embody a system's structure and enable the dynamics of system behavior. When the model is represented as a network diagram, the basic building blocks of models of complex systems are nodes (entities) and links (relationships). Note that if we were to adopt another representation (e.g., differential equations or if-then rules), the building blocks used to depict the system would be quite different.

Nodes represent agents or actors (e.g., people or firms), while links represent relationships, or ties, between actors in a complex networked system (Moody, McFarland, & Bender-deMoll, 2005). An axiomatic model must also take into account the existence of conflicting objectives among nodes (e.g. capture largest market share, minimize supply cost, etc.). Similarly, nodes in complex systems have the ability to learn and self-organize (i.e., add, remove, and change the nature of links). A robust axiomatic model would, ideally, capture this. Relationships among nodes can also be of varying nature.

Traditionally, network studies have captured flows of both tangibles and intangibles, such as raw materials, components, goods, services, information, money, and people. However, there are also numerous non-flow relationships among nodes. These often include contracts, competition, technology, geography, and industry. In the context of product and service delivery systems, there also may be a stochastic nature of supply and demand as well as changes in the system structure due to adaptation to internal and environmental factors that must be considered.

Beyond the simple indication of a relationship between nodes, there are also context-specific attributes of interest for the network models we have adopted to represent product and service delivery systems. For instance, while traditional node-link diagrams assume a single relation between two nodes, previous product and service delivery research has shown that for a pair of organizations, multiple types of relationships, or compound relationships, often may exist (Ross & Robertson, 2007). A firm may therefore be a customer, supplier, partner, and competitor of another firm all at the same time. Thus, the number of relationships can be an attribute of interest in complex systems research.

Table 3 provides a non-exhaustive summary of potentially relevant network elements and their attributes that should be considered when visualizing complex product and service delivery networks.

Element	Description
Node	Actor (Organization), Player, Entity in the Product and Service Delivery System
- Label	Actor Name (e.g. Company A, Company B)
- Type	Type or Class of an Organization (e.g. Supplier, Partner, Complementor, Competitor)
- Attribute (Class)	Industry Segment (e.g. Insurance Provider, Pharmaceuticals, Medical Equipment Supplier, Health Providers, R&D Laboratories, Automobile Manufacturer, Engine Supplier), Organization Size, Organization Revenue, Geospatial Position (e.g. Country, Location)
Link	Relation (Alliance, Partnership, JV, Buyer / Supplier / Customer); Contract; Technology Dependence
- Attribute (Class)	Strength of Relation, Type of Relation, Length of Relation, Type of Value Exchanged (e.g. Information, Raw Material, Components, Goods, Services, Knowledge, Money, Material, People)
- Direction	Directed (e.g. flow from source to destination node), Undirected

Table 3. Salient Node-Link Characteristics of Enterprise Networks (adapted from Basole, 2009).

Visualizing Complex Systems

Product and service delivery systems, or value networks, contain five types of actors: consumers, service providers, tier 1 and 2 enablers, and auxiliary enablers (Basole & Rouse, 2008). Value in such systems is created and delivered through a complex set of business-to-business (B2B), business-to consumer (B2C), and consumer-to-consumer (C2C) relationships, and influenced by the social, technological, economic and political context in which it is embedded. Figure 1 depicts the nature of such networks.

The following examples illustrate the characteristics of the retail domain and healthcare delivery domain. Specifically, we have focused on the Fortune 1000 to identify salient industry segments and companies in each segment of these domains. It should be noted that this approach inevitably eliminates many innovative small companies from the analysis. It is however our belief that this limitation is acceptable given the comparative nature of the examples and analyses we present in this chapter.

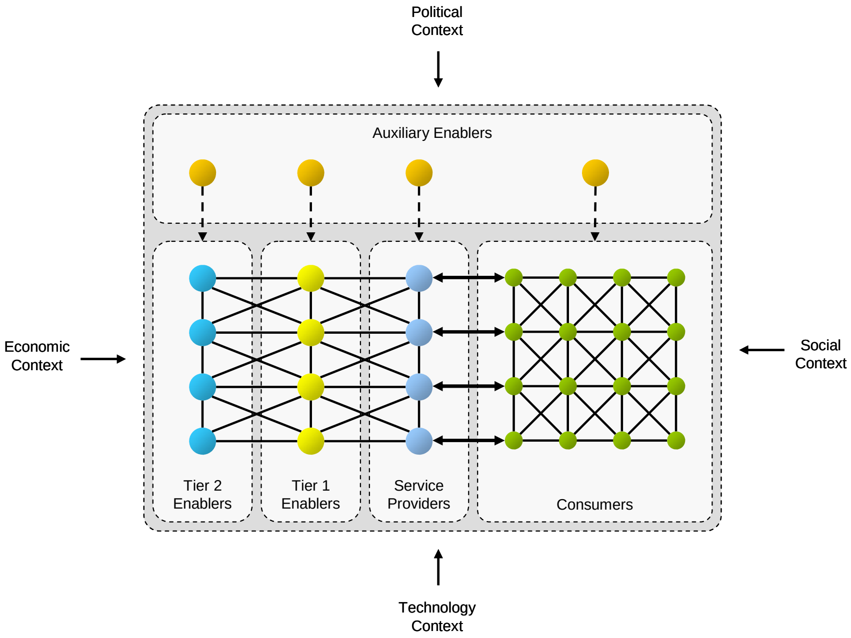


Figure 1. A Conceptual Model of Service Value Networks

Retail Example

The retail market is immense. The five markets depicted in our earlier paper (Basole & Rouse, 2008) involve roughly one-half of the Fortune 1000; retailers and their suppliers involve one-half of these companies. Service delivery systems such as *Retail*, as well as *Healthcare*, differ from product delivery systems in terms of the nature of transactions. When one buys or uses an airplane or an automobile, one can reasonably expect that after the purchase one will receive all the parts of the vehicle. In contrast, it would be very unlikely to buy one of everything in a retail store, or avail oneself of every treatment is a hospital. Consequently, the product and service delivery system (Figure 2) has a more varied set of relationships between suppliers and retailers.

As the complexity assessments in the next section indicate, *Retail* is very complex. However, as will be seen, the consumer does not have to address this complexity. A very efficient user interface has been created: stores, both brick-and-mortar and online. Increasing B2B complexity has resulted in decreasing B2C complexity. Increased convenience and decreased prices have driven consumer value (i.e., B2C value), enabled by B2B value.

Healthcare Example

The *Healthcare* value network is one of the most complex of the five domains discussed in (Basole & Rouse, 2008). This network can be described as a loose federation of independent enterprises, all trying to optimize the market from their perspective and for their benefit (Figure 3). No single enterprise or type of enterprise dominates. Further, enterprises from private and public sectors, as well as academia and nonprofit organizations, are laced throughout the value network (Rouse, 2008).

This can result in very confused customers, often receiving conflicting guidance from different players. However, this situation will inevitably change, and the Internet has enabled highly informed customers to make well-informed choices. As more information on provider performance — and availability — becomes accessible, consumers will have greatly increased leverage. It can be expected that the extreme fragmentation of the industry will not persist, if only because the projected economics of the industry as it is are not tenable.

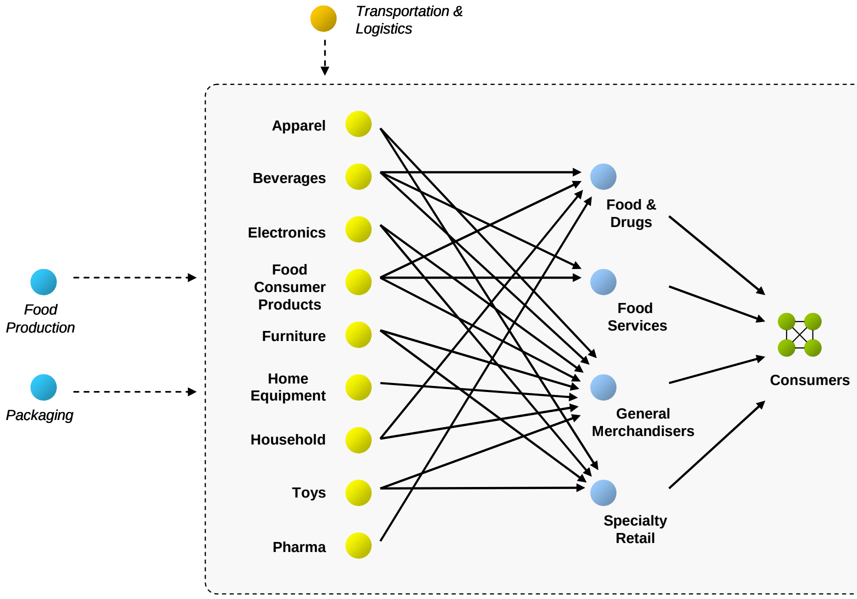


Figure 2. Retail Enterprise

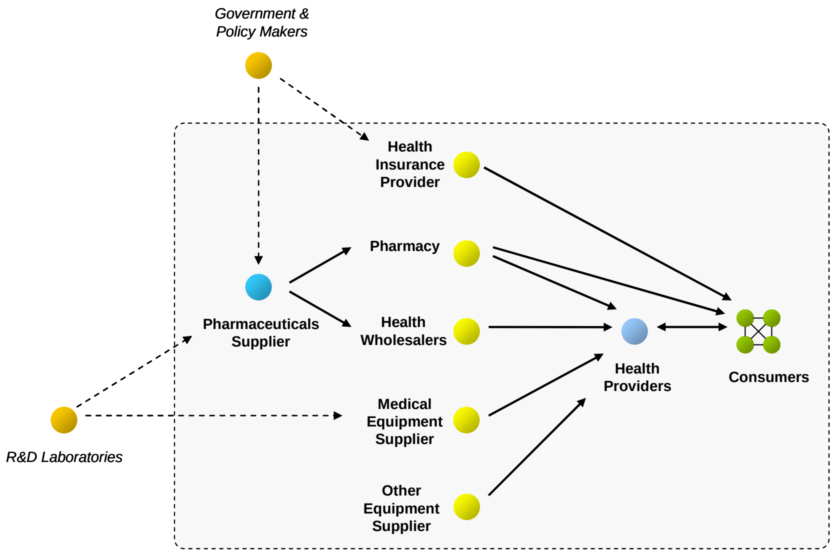


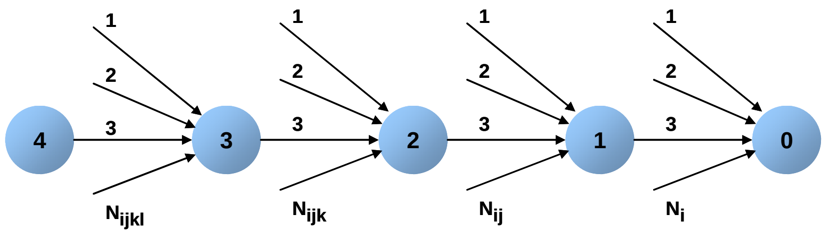
Figure 3. Healthcare Enterprise

In addition, there are a large number of providers of services with many dimensions. Consequently, service is uneven, costs are high, and consumers are often confused and frustrated. The providers and enablers that can fix the B2C value proposition, while also reducing B2C complexity, are likely to reap enormous benefits. At the same time, the push for ‘‘consumer directed’’ healthcare may result in increased complexity for consumers, which has not proved successful in the other four markets. Innovations that increase B2B complexity in order to reduce B2C complexity are more likely to be successful.

Complexity Assessment

In order to assess the complexity of networks such as depicted in Figures 2 and 3, this representation can be generalized as shown in Figure 4. As discussed earlier, the objective for which complexity is to be assessed has to be specified. The objective of interest is the state of the network. In this section, we present an axiomatic model of the complexity associated with determining network state, based on the axioms of network, probability, and information theories.

The state can be defined as the identity of all nodes involved in any randomly chosen transaction, t_m, where $m = 1, 2, 3, \ ,T$. Each type of transaction can be selected with probability pt_m. The complexity of the network can be defined as the amount of information that has to be collected to determine the state of the network, i.e., the identity of the nodes involved in the transaction of interest. To determine this, one needs to know the conditional probabilities that particular nodes are involved given the type of transaction of interest. From Figure 4, one can see that the conditional probabilities cascade from right to left depending on which paths exist from left to right. In general, not all enablers are suppliers of all providers. Therefore, these conditional probabilities are not uniform.



N_i = No. of 1st tier suppliers to ith product/service outlets

N_{ij} = No. of 1st tier suppliers to ijth product/service outlets

N_{ijk} = No. of 1st tier suppliers to ijkth product/service outlets

N_{ijkl} = No. of 1st tier suppliers to ijklth product/service outlets

Figure 4. General Network Model

Given knowledge of the conditional probabilities of interest, equation (3) shows how complexity *C* can be calculated using Shannon’s calculation of entropy in information theory (Shannon, 1948). This measure has since been applied in domains ranging from failure diagnosis (Golay, Seong, & Manno, 1989) to manufacturing (Deshmukh, Talvage, & Barash, 1998; Kaimann, 1974) to sociology (Butts, 2000) as a measure of the observational and/or computational effort involved to assess the state of a system. Indeed, all measures of complexity are based on the characteristics of a representation of a system (Rouse, 2007b), with network representations the most common (Casti, 1995).

$$C = \sum_{m=1}^{T} pt_m \left\{ \begin{array}{l} \sum_{i=1}^{N_i} - p(n_i \mid t) \log\left[p(n_i \mid t_m)\right] \\ + \sum_{i=1}^{N_{ji}} - p(n_j \mid n_i t) \log\left[p(n_j \mid n_i t_m)\right] \\ + \sum_{i=1}^{N_{jik}} - p(n_k \mid n_i n_j t) \log\left[p(n_k \mid n_i n_j t_m)\right] \\ + \sum_{l=1}^{N_{jikl}} - p(n_l \mid n_i n_j n_k t) \log\left[p(n_l \mid n_i n_j n_k t_m)\right] \end{array} \right\} \tag{3}$$

where N_i, N_{ij}, N_{ijk} and N_{ijkl} are the number of nodes at each “tier” of the network and $p(n \mid n\ n\ n\ t)$ is the conditional probability that a particular node is involved given the transaction is type t_m, and the logarithm is to the base 2.

The measure of complexity resulting from the above equation is binary digits, or bits. Intuitively, it represents the number of binary questions one would have to ask and have answered to determine the state of a value network. This measure is not without subtlety. For example, if one claims, as we do below, that the complexity of the entire *Retail* market is over 30 bits, there will undoubtedly be many skeptical responses. However, once one explains that this means that more than one billion binary questions would be needed to determine the state of the system, people begin to understand the implications of this measure of complexity.

Note that equation (3) has repeated terms of the form $– p \log p$. If the network of interest included only one upstream node, with probability p of being involved in the transaction and $(1-p)$ of not being involved, then the complexity calculation would be of the form $– [p \log p + (1-p) \log (1-p)]$. This value is maximum for $p = 1/2$. In general, if there are N upstream nodes and the probability of each being involved in a transaction equals $1/N$, then uncertainty and, hence, complexity is maximized.

This observation implies that complexity, as we have defined it, can be decreased by greatly simplifying supply chains, i.e., having only one supplier for each element of the system. Unfortunately, this tends to reduce variety and can lead to increased risk of losing the sole supplier for an element of the system. A better strategy may be to allow increased complexity as long as it can be managed by, for instance, enhanced back office information systems. Indeed, this has been the strategy in *Retail*.

Using publicly available data from the Fortune 1000, we were able to identify the number of companies in each node of Figures 2 and 3, as well as for three other domains – aerospace, automotive, and telecom (Basole & Rouse, 2008). The probabilities associated with each company being involved in any given transaction were calculated in one of two ways. The predominant way was simply to estimate the probability as one divided by the number of supplier or manufacturers. In a few cases, we adjusted the probabilities to reflect the fact that a Fortune 1000 supplier must be supplying at least one Fortune 1000 manufacturer. The results are shown in Figure 5.

Several observations are important. First, highly fragmented markets are much more complex than highly consolidated markets. There are relatively few aerospace and automotive providers compared to retailers and consumer products companies. While manufacturers of airplanes and automobiles are likely to claim that their products are complex, consumers do not have to address this complexity and these industries benefit from this. Many more people fly on airlines and drive automobiles than design and develop such systems.

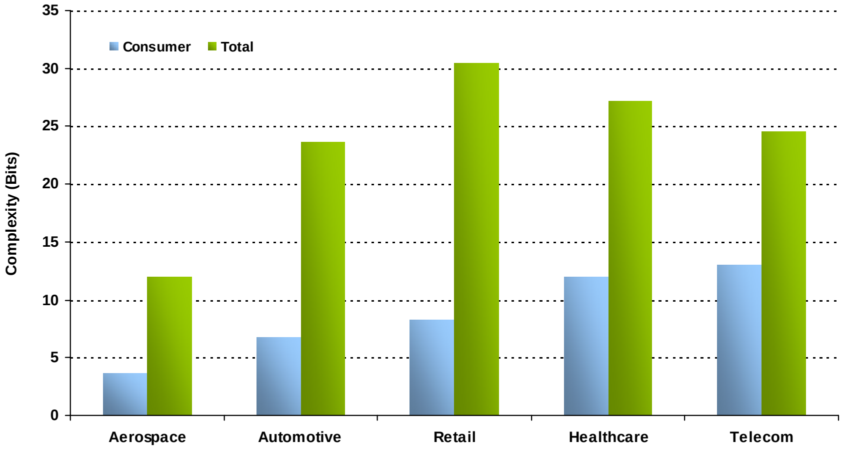


Figure 5. Complexity Assessments

Second, consumer complexity can be reduced by either market consolidation, so there are fewer choices, or by increased B2B efficiency that reduces B2C complexity. The aerospace and automotive industries are examples of the former and the retail industry is an example of the latter. Note that the telecom industry is clearly employing both mechanisms, while healthcare, via consumer-directed healthcare, is moving away from both mechanisms. This suggests that new intermediaries will emerge in healthcare to manage complexity for consumers.

Of particular interest is the comparison of *Retail* and *Healthcare*. *Retail* is the most complex domain because, as indicated earlier a very large number of companies are in the retail industry. However, the consumer does not experience this complexity because of a high degree of back office automation. *Healthcare* includes fewer enterprises, but the lack of integration results in consumers having to deal with much more of the network. If *Retail* operated the same way as *Healthcare*, buying a toaster or can opener at a retailer would result in the consumer receiving ten or more bills from suppliers of components, probably many months later, with little explanation of why this supplier was involved in creating the appliance. This would not make for happy consumers.

Note that this conclusion regarding the complexity of *Healthcare* is consistent with our earlier conclusions based on more holistic analyses. The fragmentation of this domain contributes greatly to its complexity, especially for consumers. Thus, we see that the qualitative and quantitative analyses can be quite complementary.

USE AND VALUE OF MODELS

There are many benefits of developing models of complex systems. In general, a model tends to serve as an abstraction, or approximate representation, of phenomena of interest. Models enable researchers, designers, and managers to explicitly identify, describe, and analyze the key underlying elements, principles, and properties that define and shape complex systems.

The resulting models thus allow us to illuminate core dynamics, predict future states, suggest dynamical analogies, identify uncertainties, discover new questions, and challenge existing theories (Epstein, 2008). They also enable us to formulate and address tradeoffs and suggest efficiencies.

Beyond the value in the final resulting model, there is tremendous, and often ignored, value in the modeling process itself; it provides critical insight into the salient underpinnings of product and service delivery systems and exposes the importance of the enabling assumptions. In other words, modeling of complex systems enables us to open dialog and communicate our cognitive map of the product or service delivery system of interest.

By laying out complex system elements and their relationships in detail, we are able to study why, how, and potentially when observed and anticipated phenomena may occur. In the context of product and service networks, for example, it allows us to study policies, interventions, and strategies at various points and stages of delivery life cycles. It enables researchers and managers to make informed tradeoffs across design and development, manufacturing and assembly, operations, maintenance and consumption, as well as suggest efficiencies and strategies to mitigate risks. It also enables uncovering the complexities that either accelerate or impede the product and service delivery network. Consequently, complex system models of product and service delivery networks enable us to better design and manage these.

Furthermore complex system models enable us to benchmark processes, enterprises, and markets and make competitive comparisons. Such comparisons were central to the results presented in this chapter. Models can also provide insights into the dynamics of innovation and the factors that lead to competitive advantage in product and service delivery networks.

Last but not least, developing models of complex systems also provides the basis for visualization of ecosystems and their dynamics. Using visualization, decision and policy makers can analyze and understand the structure of complex enterprise systems, identify roles (e.g. hub, broker, bridge, niche) that actors play, and the potential evolution of the industry (Basole, 2009).

Mapping actor relationships enables us to understand and identify patterns and structures of firms engaged in innovation and value creation. The use of visualization models also provides one a platform to differentiate complex networked systems by purpose, in terms of the ways firms compete and collaborate (Kambil, 2008).

Visualization also enables one to explicitly map actors into a decision space. We can see how actors relate to each other. Identifying coordinates within a visual framework will provide insight into the nature of firms' placements, what these positions mean, and consequently provide a more systematic way to understand the structure and evolutions of inter-firm networks over time.

In summary, complex system models have tremendous value for both researchers and practitioners. They enable exploration, identification, discovery, and communication of complexities that previously were often ignored. The knowledge gained can both extend the state of the art and provide competitive advantage.

CONCLUSIONS

This chapter has discussed the complexity of product and service delivery systems. This involved considering holistic views of complex systems in the context of several public-private systems. A notional model of complexity was introduced that relates complexity to the number of enterprises in a domain and the levels of integration required for these enterprises to function successfully. Reductionist views of complexity were also considered. The basic premises underlying axiomatic models of complexity were discussed including typical definitions of the structure and state of a system. An information theoretic model was introduced for calculating complexity in terms of the number of bits of information that must be processed to assess the state of a complex system. This model was applied to assessing the complexity of several enterprise domains. The chapter concluded with a discussion of the use and value of models of complex systems.

The overarching conclusion of this chapter is that understanding of complex systems can be advanced by both holistic and reductionist approaches. Indeed, these approaches are complementary as illustrated by our conclusions regarding the complexity of *Healthcare*. We can learn a lot by considering both the forest and the trees. The holistic view enables seeing emergent phenomena and connections, while the reductionist view enables seeing how the pieces of a network come together to achieve the objectives for which they were designed.

The reductionist results presented in this chapter are predominantly quantitative, while the holistic results are rather qualitative. The reductionist complexity model, built upon axioms of network, probability and information theories, enabled deduction of the complexity metric of bits of information needed to determine network state. In contrast, the holistic complexity model relied upon knowledge of the broad characteristics of particular complex systems. Had we sought data on these characteristics, this model could have been parameterized, quantitative results measured, and statistical inferences made. The result would have been an empirical holistic model.

It would also be possible to frame an axiomatic holistic model. This might take the form of a macroeconomic model perhaps represented in terms of differential equations, from which characteristics such as stability and response times could be deduced. Thus, the distinction of deduction vs. inference, while very important, is not synonymous with holism vs. reductionism, nor qualitative vs. quantitative approaches. Perhaps the crucial distinction is between deriving conclusions from basic principles versus inferring conclusions from observations of phenomena. Our basic argument in this chapter is that both approaches are needed and complementary.

It is also important to revisit a basic premise of the model of complexity presented here, namely, that complexity can only be modeled relative to the intent of the modeler – in our case, determining the state of the network. The complexity metric employed does not capture the effectiveness, strength, or basis of relationships between entities in the system; it merely captures the conditional probability that two nodes are linked. For example, two nodes may be connected with each other based on a supply relationship, but the extent to which this link is effective is not reflected in our model. Hence, we can have a network that is very complex but ineffective (e.g., *Healthcare*) or very complex and extremely effective (e.g., *Retail*). Of course, we might also have networks low in complexity, but very ineffective in some cases and very effective in others.

This issue was not as limiting for the holistic model because we could incorporate a broader set of knowledge into the line of reasoning. We know that *Healthcare* is ineffective and the reasons underlying this assessment (Reid, Compton, Grossman, & Fanjiang, 2005; Rouse, 2008). Similarly, we know the overhead burden imposed by government oversight of *Defense*. Thus, to a great extent, the holistic model was based on simply organizing a wealth of knowledge of the characteristics of these domains, finding common attributes among these characteristics, and then positing how these attributes would affect complexity. In other words, we organized observations rather than deriving results.

These contrasts raise questions of how best to represent and visualize complex product and service delivery systems. How can one represent and visualize the nature of relationships among entities in order to derive – or just observe – the effectiveness of a network? How might one assess current effectiveness or project future effectiveness? How might one infer or deduce likely areas of future innovation from the nature of the entities and relationships portrayed?

Our sense is that no single type of representation or visualization will be sufficient. The analyst or the decision maker will need multiple views of the value network. At a minimum, these views will need to include at least one holistic view and at least one reductionist view. Put another way, at least one top-down view and one bottom-up view will be needed. Beyond this minimum, we expect that the necessary views will include financial, material, behavioral, social, and geographical portrayals. With such a portfolio of views, people will be able to truly understand complex value delivery networks.

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