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# The Analysis of Networked Supply Chain Problem

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## ABSTRACT

The Internet-based electronic markets bring together hundreds of thousands of businesses and millions of individual consumers in market. As firms revamp their supply chain models by going online and outsource part of their process steps to better-able partners, the supply chains are no longer linear and become more complex. The networked supply chain is one of the most loosely defined problems where analysis models are not established. This study defines the networked supply chain problem, and then uses the traveling salesman problem (TSP) framework to take a close look at the interaction between computational complexity and economic considerations in the networked supply chain. The application of standard computer-science theory of computational complexity to the networked supply chain problem becomes important theoretical and empirical aspects of the modeling process in the networked supply chain.

***Keywords:*** computational complexity, networked supply chain, search cost.

## 1. INTRODUCTION

Production of almost any complex product consists of acquiring various raw materials and other components and crafting them, with each step adding value as the product wends its way towards its ultimate consumer (Porter, 1980). In order to be successful in a pull economy where the customer orders trigger the production of goods, firms must stress flexible business processes via shorter production runs that results in wide variety of customized products, each differentiated to solve unique set of customer requirements. Firms must practice process fragmentation, which is characterized by differentiated products, manufacturing versatility, and process innovation. Process fragmentation permits firms to outsource part or all of their process steps to better-able partners and extended the procurement to global suppliers, sub-assembly manufacturers and contract operators. The total market is effectively broadened as more and more submarkets are created through continuous nicheing (Robert, 1992). On the other hand, the advance in information and telecommunications technologies allows firms to extend their systems integration all the way both down and up the chain to coordinate their supply chain activities in real time with suppliers, partners, and customers. Firms and individuals increasingly participate in electronic markets as customers, suppliers, intermediaries, and partners. Electronic markets change the way firms integrate their supply chains and interact with their suppliers, partners, and customers. To get the real benefits from electronic markets, firms enlarge the number of participating partners in their business processes and thus create networked supply chain. Networked supply chain lowers entry barriers and results in more and more participants in the network. These factors are the motive force of the development of networked supply chain.

Networked supply chain is a linked network of firms that provides the connections and technologies to support the firms in many ways to cooperatively plan, design, manufacture, distribute and support the delivery of goods across end-to-end supply chain headed toward a designated customer. It also provides the firms with more opportunities to satisfy a variety of customer demands. A main shift in the sourcing dynamics is that firms have the option of considering a large number of suppliers and partners in their supply chains. In other words, networked supply chain provides many more degrees of freedom in how products and services can be configured and selected, how resources can be obtained and organized, and how goods can be produced and distributed. As a result, the networked supply chain is becoming increasingly combinatorial. The combinatorial nature of networked supply chain gives firms enough freedom and sufficient resources to explore new areas of growth and new ways of doing business. However, the complex networked supply chain also poses challenges in understanding the implications of possible supply chain design, the market structure and efficiency, and management actions. Unless managers understand how they are involved their firms in the electronic market when they make a decision related to the networked supply chain, they run the risk of making the wrong decisions.

One of the major challenges is the computational complexity involved in developing a networked supply chain. As the supply chain become more complex and larger, a firm has to spend more and more effort and time to find the optimal or appropriate choice of a suitable set of business partners and suppliers. The effect of computational complexity of networked supply chain on the search cost is not well understood in business area because there is no available model and analytical technique that makes the phenomenon amenable to simple analysis. In fact no model will ever capture the full complexity of networked supply chain. Interdisciplinary research from economics, management science, information systems, and computer science is needed to study the interaction between computational and economic factors. The major task of this study is taking a close look at the interaction between computational complexity and search cost in a networked supply chain. This study applies the traveling salesman problem (TSP) model to the networked supply chain problem with analogous results in the behavior of search cost. The major theme of this paper is to demonstrate how TSP model in computer science can be used to provide insights into the analysis of networked supply chain in business.

The remaining of the paper is organized as follows. Section 2 discusses the transformation of the supply chain. Section 3 defines the networked supply chain problem and explains the computational complexity of the problem. Section 4 uses the TSP framework to analyze the relationship between computational complexity and search cost in the networked supply chain, and discuss the implication of the complexity on market behavior and firms' governance choices. The final section concludes this paper.

## 2. TRANSFORMATION OF SUPPLY CHAIN

Markets have three main functions: matching buyers and sellers; facilitating the exchanges of information, goods, service and payments associated with market transactions; and providing an institutional infrastructure that enables the efficient functioning of the market (Bakos, 1998). Internet-based electronic market leverages information technologies to perform these functions with increasing effectiveness and decreasing transaction costs.

Economic theory supports the argument that the electronic market holds great promise for improving interorganizational coordination and interfirm transactions in market settings (Bakos, 1998; Bryniolfsson and Smith, 2000). One of the most common predictions about the electronic market is that electronic Ü±rket encourages "frictionless commerce" by reducing transaction costs that formerly made it more difficult to find and conduct business with new trading partners. Market friction is a general economic concept that describes the forces that shift the equilibrium of the market away from the competitive equilibrium. One major factor that cause transactions not occur at competitive market equilibrium is the transaction costs. Firms organize themselves to minimize transaction costs so that they can be more economically efficient (Coase, 1937). Transaction costs can be used to describe why firms are created and what distinguishes the boundary of one firm from the boundary of another (Alchain and Demsetz, 1972; Demsetz, 1968; Williamson, 1979). Procuring a product can be done within the boundary of the firm or done as a market transaction between firms. Whichever organizational mode has lower transaction costs is preferred. If transaction costs decrease between firms more than they decrease within the firm, then there will be an organizational shift from intra-firm transactions to market transactions. If the reverse is true, there will be more intra-firm transactions and fewer market transactions.

Information technologies are changing the constraints imposed by transaction costs. As transactions are conducted electronically, they cost much less than physical world transactions. When information technologies are used to facilitate market exchange, the overall transaction costs may decrease because of lower search costs (Bakos, 1997), lower coordination costs (Malone *et al.*, 1987), and lower payment processing costs (Sirbu and Tyger, 1995). Lower external transaction costs should result in greater horizontal fragmentation of business processes with increased specialization. "Fragmentation", also called "outsourcing" in business literature, is defined as the splitting of a production process into two or more steps that can be undertaken by different firms but that lead to the same final product. When a production process is split into parts, it can be done in a wide variety of ways.

The increase in customization and personalization of product offering, and increased competition created by globalization and decentralization require firms to be more flexible in business processes. Process flexibility is needed to respond fast to market changes, modify production processes at will, adopt innovative business models easily, and catch opportunities unavailable to slower firms. Process flexibility becomes a core competency. Fragmentation is a key technique to achieve process flexibility. Information technologies make the fragmentation become possible in industries.

Fragmentation is a diverse phenomenon, spanning multiple markets by industries, by regions, by countries, and by channels. Low entry cost for new entrants and rapid coordination among various firms dramatically increase the number of potential firms that can be involved in a given product fulfillment process. The benefits realized by the participants increase as more firms participate the networked supply chain, leading to network externalities (Katz and Shapiro, 1985). The surge of networked supply chain is a result of firms' pursuit of customer satisfaction and the growing competition for customers. The seamless network of customer choice and fulfillment capability is fast enough and flexible enough to respond to the rhythms of the market and add value beyond cost efficiency. The structure of supply chain is transformed into combinatorial one where firms can organize a "virtual bundle" of resources to match customer needs and support new pricing strategies in a variety of ways. When determining their product mix, firms must decide which product components or features will be included in each product offering. These decisions are driven by the relative cost of different resource bundles. Finding optimal bundle for each prospect creates a challenge. Each product has its own specific goals and requirements. Each channel has its own cost and capability. Therefore, the networked supply chain becomes a mish-mash for some firms, as they try to search through the multiple possibilities to find the best supply chain configuration. Determining the optimal resources bundle in a networked supply chain can be computational challenging.

## 3. NETWORKED SUPPLY CHAIN PROBLEM

A networked supply chain builds seamless direct relationships between suppliers, manufacturers, business partners, distributors, and customers. Within each of processes, many related firms take part, creating more relations–and transactions among them. This situation can be represented by a diagram with a node for each participant and a line segment joining two nodes for each potential transaction link tagged with a transaction cost. Fig. 1 shows an example of networked supply chain. In the context of network, determining an optimal supply chain becomes a combinatorial optimization problem. In general, the primary task studied in combinatorial optimization problems has been the choice of a best configuration to achieve some goal.

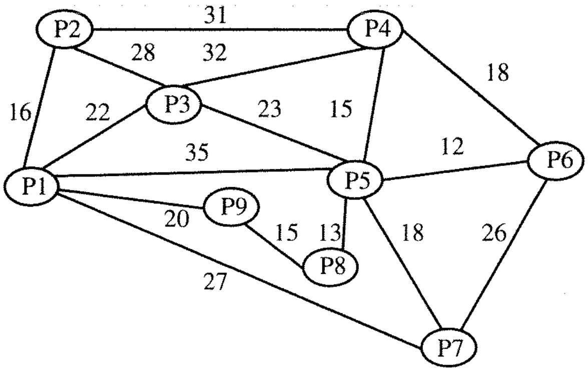


**Fig. 1.** An example of networked supply chain

The *networked supply chain problem* (NSCP) can be defined as "given a set of participants $N$ in a networked supply chain and a final product to be provided to the ultimate consumers, what is the transaction stream configuration that delivers the product with the minimum transaction cost." A *participant* is any firm or individual involved in any of the transaction process. The *final product* is the resulting item of a series of transaction activities. By *transaction* we mean some form of economic activities between different participants. The *transaction stream configuration* consists of the participants that need to be involved in a series of production processes in order to produce the final product and the order in which these participants need to proceed. For certain pair $v$, $w$ of participants, there is a known positive transaction cost $c(v, w)$. Let $c(s)$ denote the total transaction cost of particular transaction stream configuration $s \in S$, the NSCP can be formulated as follows:

$$\min c(s) = \sum_{(v,w)\in N} c(v,w)$$

The configuration space $S$ consists of all possible transaction stream configurations. The goal of the NSCP is to find a transaction stream configuration $s^*$ with minimal total transaction cost $c(s^*)$. The transaction stream configuration $s^*$ is called an *optimal transaction stream configuration*. Networked supply chain that allows firms to find optimal transaction stream configurations can lead to more economically efficient resource allocations, but determining the optimal configuration is extremely difficult. There are too many configurations in the configuration space, and looking at all configurations would be expensive. Therefore, the networked supply chain creates the computational complexity.

Computational complexity refers a condition where it is very costly, perhaps impossible, to consider the complete configuration space. While a networked supply chain can create considerable benefits, such as flexible manufacturing and agile supply chain, the successful implementation of a networked supply chain requires overcoming the computational complexity of the problem. The NSCP can be proved to be a *NP*-complete problem. The computational requirement for a *NP*-complete problem is such that linear increase in the size of the problem results in exponential increase in the time needed to solve the problem. Even with abundant computational power, exponential demands can soon collapse any existing computer. The traveling salesman problem (TSP) is one of the best-known *NP*-complete problems in computer science. A nice collection of papers tracing the history and research on the TSP can be found in Lawler *et al.* (1985).

In the general form of the TSP, we are given a finite set of cities $V$ and a distance $d(i, j)$ between each pair of

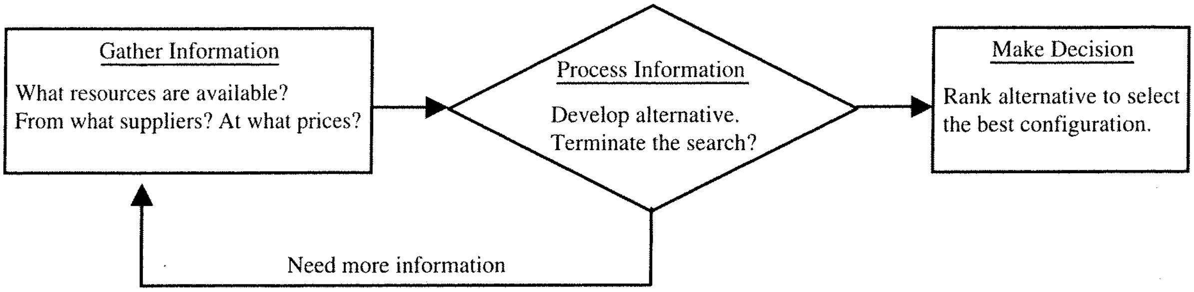


**Fig. 2.** A diagram of firm's search process for networked supply chain

cities $i, j \in V$. A *tour* is a circuit that passes exactly once through each city in $V$. The goal of TSP is to find a tour of minimal length. Let $d(t)$ denote the total distance of a tour $t$, the general TSP can be defined as the following formula:

$$\min d(t) = \sum_{(i,j) \in V} d(i,j)$$

It would not be difficult to develop a search algorithm for the TSP, which finds the optimal tour by trying all possible tours. The issue is not whether the algorithm exists to compute the solution but what is computational requirement. If one has 100 cities, trying all of alternative tours require trying the 100 factorial combinations (that is, $100 \times 99 \times 98 \times \ldots \times 3 \times 2 \times 1$ or $9.3 \times 10^{157}$). If we need one nanosecond ($=10^{-9}$ seconds) to evaluate each alternative, then the complete problem would be solved in $3 \times 10^{141}$ years! What makes exponential problem hard to manage is that a little increase in the problem size results in a much greater increase in the computational requirement. For example, if we increase the number of cities from 100 to 150 (an increase of 50%), the computational requirement for this problem would be $1.8 \times 10^{246}$, an increase of $10^{105}$ times.

Indeed, from a practical point of view, *NP*-completeness means that there is no known algorithm that can solve every instances of this problem in a time growing less than a power of problem size, and it is unlikely that such an algorithm can be found (Garey and Johnson, 1979; Papadimitriou, 1994). The *NP*-completeness and intractability of this type of optimization problems have led many researchers to employ heuristic search techniques. A *heuristic* seeks good solutions at a reasonable computational cost without being able to guarantee optimality, or even in many cases to state how close to optimality a particular feasible solution is (Reeves, 1993).

Local search heuristics are a widely used general approach to find reasonable solutions to *NP*-complete optimization problems. Typically, a local search algorithm starts off an initial configuration and then generates a sequence of iterations. Each iteration consists of a possible transition from the current configuration $s_i$ to a new configuration $s_j$ selected from the neighborhood $N(s_i)$ of $s_i$. The neighborhood search property makes a local search process locally convergent, that is, the search trajectory converges to a point that may not an optimal configuration. This point is usually called *locally optimal configuration*.

In a networked supply chain context, a firm would indeed undergo a local search process, as illustrated in Fig. 2, in attempt to find the best transaction stream configuration. Because all people have bounded rationality and the networked supply chain is too complex for their cognitively limited minds, the decision makers can not take into consideration all possible relationships. Therefore, they perform local heuristic search to look for good, but not necessary optimal, configuration in the complex network. Real-world search heuristics are based on the user-predefined rules to determine how a search is initiated, refined, processed and eventually terminated. The rules are constrained by budget limitation, desired search expenditure, and overall satisfaction with the search outcome. The decision maker can determine only the quality of a new configuration relative to the ones he/she has already observed. At each period, the decision maker can either accept the current best configuration or continue to search for a better configuration. Finally, the decision maker is to select the overall best configuration from the observed set. If a decision maker increases his effort in searching for better configuration, the quality of his search outcome may improve, but the search cost increases as well. In general, there is a trade-off between search cost and expected satisfaction (Todd and Bensbasat, 2000).

The NSCP and TSP have several similarities. First, both problems can be modeled as a graph problem by considering a graph $G = (V, E)$, and assigning each edge $e_{ij} \in E$ the cost $c(i, j)$, where $V$ is the set of notes and $E$ represents the set of edges in the graph. Second, each problem involves selecting a set of edges connecting nodes. Third, the number of feasible solutions is far too large to consider them all in a reasonable amount of time. Fourth, local search heuristics are often used to look for the good but not necessarily optimal solutions. Although TSP may not be a suitable model of NSCP, it can be used as a framework for presenting the computational complexity

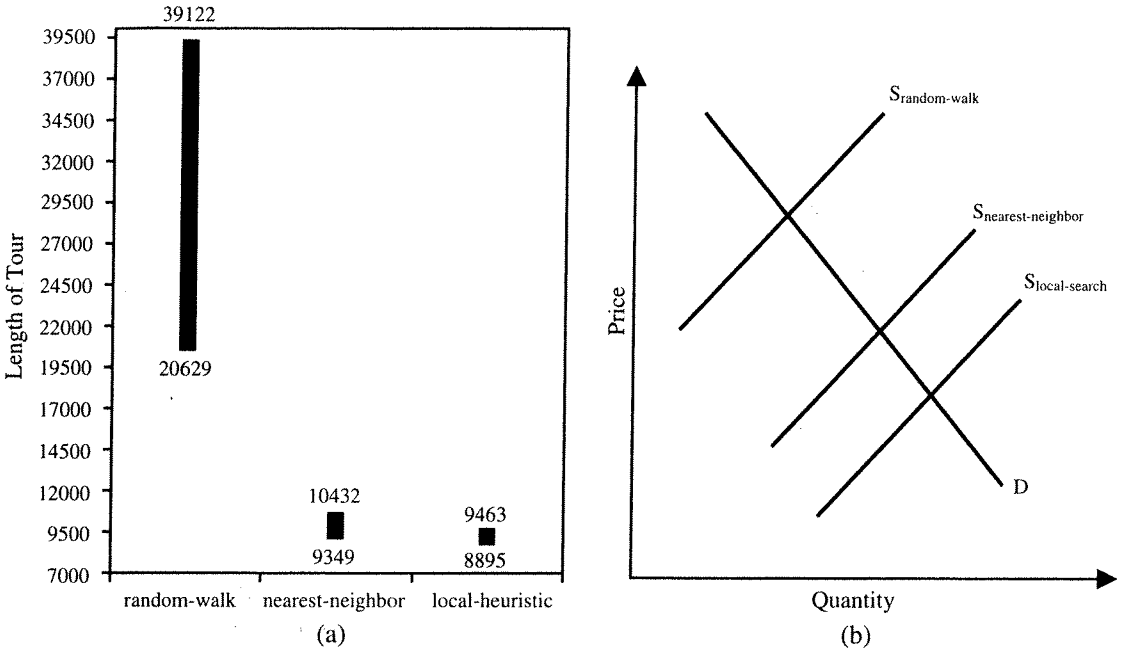


**Fig. 3.** (a) The performance of random-walk, nearest-neighbor and local-search on the 1000-city TSP. (b) The effect of the search outcomes on the market

of NSCP, thus providing valuable insights about the behavior of more complicated networked supply chain.

This study generates five uniformly distributed TSP instances with 1000, 2000, 3000, 4000 and 5000 cities, respectively. The distance element *d*(*i*, *j*) is assigned a random number in the interval [1, 100]. This study uses these TSP instances to examine the implications of computational complexity of a networked supply chain on search cost and market efficiency.

Networked supply chains can be analyzed at different levels. Most strategic management research has been focused on interfirm relationship at the dyadic level, i.e., relationships between pairs of firms have been studied one at a time. This level of analysis would most appropriate for researchers interested in issues such as partner motivation and the dynamics of specific interfirm relationships. Another possible unit of analysis is the overall network comprising all relationships among the participants in the networked supply chain. Analysis at the network level can help us understand the patterns of strategic alliance activities in an industry and overall market performance in the economy, thereby throwing light on some of the market-level drivers of the phenomenon.

The interfirm relationships in a networked supply chain can be constructed in many different ways. The interfirm relationships can be built in an *ad hoc* way. Each firm at each layer of suppliers randomly selects its suppliers. This method is equivalent to the "random-walk search" in TSP. It is not possible to claim that this algorithm will return an optimal solution. Another improved method is the so-called "nearest neighbor search" in TSP. You pick a starting city, and then go to the nearest city not yet visited. Continue from there to the nearest unvisited city. Repeat this until all cities have been visited. In the context of networked supply chain, a firm selects the best supplier from a group of potential suppliers at one layer, and that supplier selects its best supplier from the next layer of suppliers. Continuing in this way, a transaction stream configuration is formed. In TSP, although each move in the nearest neighbor search is locally the best possible, the overall result can be quite poor (Johnson and McGeoch, 1997).

The extreme way is to check all possible transaction stream configurations and find the best one. However, if a large number of firms are involved in the networked supply chain, it would be not possible to find the optimal configuration in a reasonable time due to the computational complexity. As an alternative method, a local heuristic search can be used to find a good, but not necessarily optimal, transaction stream configuration in a networked supply chain.

Fig. 3(a) illustrates the search results using the random-walk search, nearest-neighbor search and local heuristic search on the 1000-city TSP instance, respectively. In each search method, we assume that 10 salesmen construct their tours independently. In random-walk search, the 10 salesmen found their tours with lengths in the range [20626, 39122] with 28976 in average; in the nearest-neighbor search, the lengths of the found tours are in the range [9349, 10432] with 9807 in average; in the local heuristic search, the found tours are in the range [8896, 9463] with 9206 in average. Usually, the

**Table 1. Iterations and better solutions**

| Iteration | 1000-City | 2000-City | 3000-City | 4000-City | 5000-City |
|---|---|---|---|---|---|
| 100 | 61 | 71 | 75 | 79 | 84 |
| 1,000 | 207 | 354 | 413 | 465 | 532 |
| 10,000 | 240 | 447 | 521 | 658 | 746 |
| 100,000 | 251 | 472 | 609 | 774 | 861 |
| 1,000,000 | 252 | 478 | 637 | 823 | 929 |

local heuristic search generates better solution and smaller variation than the other two approaches. The result in Fig. 3(a) implies that if a firm tries to optimize transaction stream configuration at overall network level, it could obtain a better supply chain. Firms' search methods could have a significant impact on market equilibrium and allocational efficiency, as illustrated in Fig. 3(b).

## 4. COMPUTATIONAL COMPLEXITY IN NETWORKED SUPPLY CHAIN

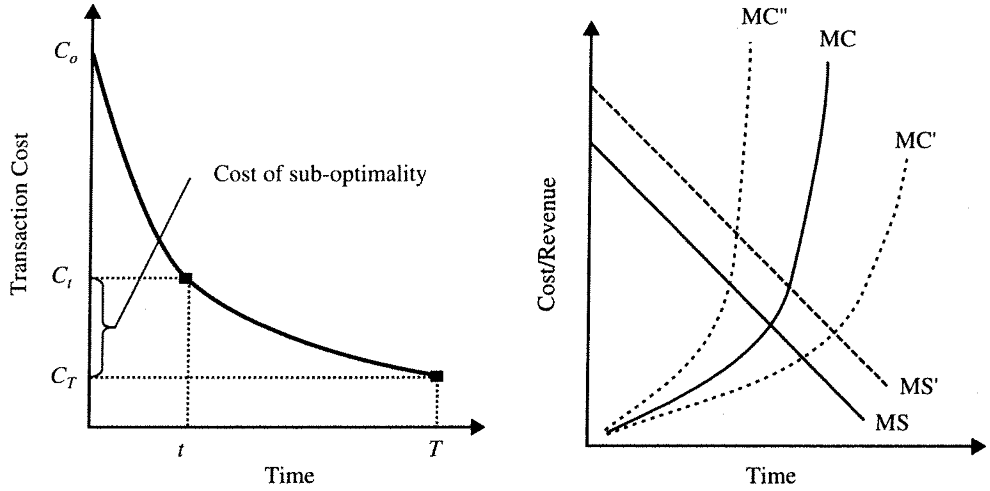
In today's economy, a key challenge for a firm is to develop an effective and efficient supply chain. The real competitive advantage may belong to the firms that have the capabilities required to identify the optimal or near-optimal transaction stream configurations. If the search cost is zero, a firm would always conduct search when it attaches a positive probability to the event that a new configuration has a strictly lower cost than the current configuration. In that respect, all firms would find their optimal transaction stream configurations and the market would realize the highest level of efficiency.

In the classic economic model of market, efficiency is maximized when all firms find their optimal configuration. Frequently, economic models assume that trade can be transacted without friction, and study the market under the zero-search-cost assumption and atomistic market structure. The information technology artifact is usually treated as a black-box by simply assuming that it has capability to eliminate search cost. One of the most prominent claims of electronic market is the approximation of the market to the ideal of perfect market with the help of information technology. Past research indicates that the Internet technologies and electronic market reduced search cost (Bakos, 1997; Malone *et al.*, 1987, Smith *et al.*, 2000). However, computational complexity theory predicts that the complexity of electronic market will lead to higher search cost. The market efficiency will be shaped by the trade-off between the search cost and search quality. Therefore, the realistic vision of networked supply chain can only be understood by understanding the computational complexity of the NSCP.

When using heuristic search technique to find the optimal solution, we conduct iterative search process. In general, during the search process, the more iterations we perform, the better solution we can obtain. But how many iterations are enough? It is perhaps somewhat surprising that there does not yet exist a useful convergence theory for this question. Table 1 illustrates the result of an experiment. This experiment applied the 2-opt algorithm on the five TSP instances. The 2-opt algorithm is a popular local heuristic search technique for TSP (Lin, 1965). One million iterations are performed on each instance respectively. The number of better solutions found during $10^k$ ($k = 2, 3, \ldots, 6$) iterations was recorded. We can see that, for the 1000-city instance, 240 better solutions are found in the first 10000 iterations, 11 better solutions in the next 90000 iterations, but only one better solution found in the next 900000 iterations. For the 5000-city instance, 861 better solutions are found in the first 100000 iterations and 68 more better solutions found in the next 900000 iterations. How many more iterations should we perform to find one more better solution? The decision maker is faced with a dilemma whether to accept the current best solution and thereby terminate the search process or continue searching in the hope of obtaining a better configuration later. Unfortunately, the optimal cutoff point cannot be expressed by a simple formula or rule. The stopping criteria used by the decision maker are sensitive not only to the characteristics of the expected optimality but also to the search cost and the problem size. The problem outlined above really exists in practice.

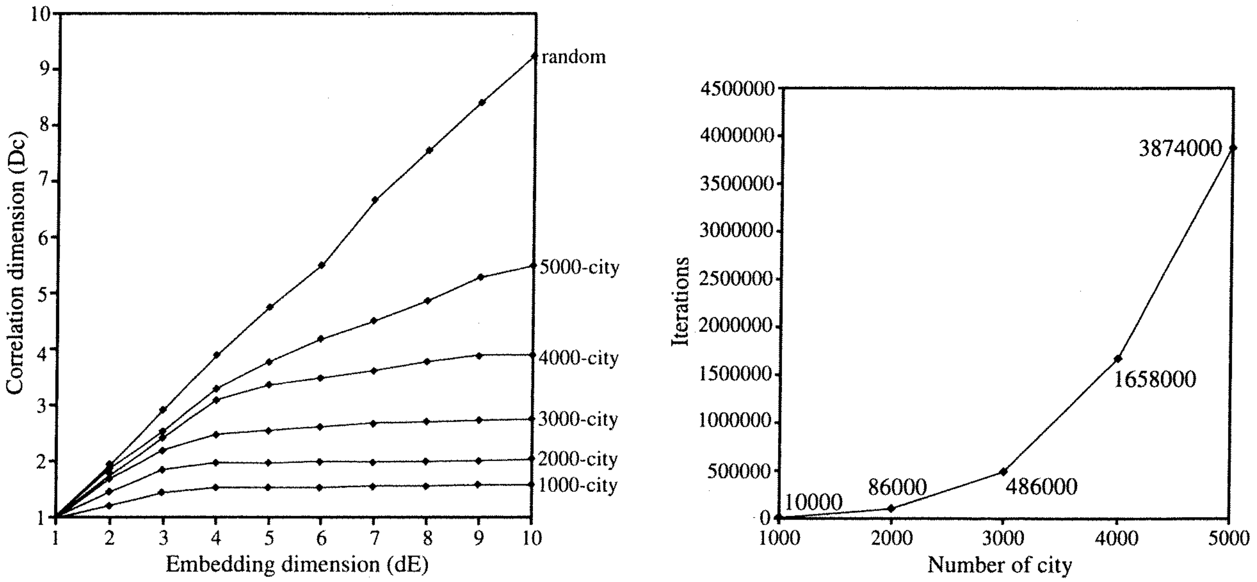
Let $t \in [1, 2, \ldots, T]$ denote the time that the firm has to spent to find the optimal transaction stream configura-tion, where $T$ is the time needed to obtain the optimal configuration that has transaction cost $c_T$. After spending time $t$, the firm's configuration vector is $s_t = (t, c_t)$, where $c_t$ is the lowest transaction cost the firm has found. At this point, the firm may either stop searching and accept ct or continue to search. If the firm stop search at $t$, the difference between $c_t$ and $c_T$ is the *cost of sub-optimality*, as shown in Fig. 4(a). The cost of sub-optimality could be one major factor that cause transactions not occur at competitive market equilibrium.

If the firm chooses to continue searching, it will expect that the marginal saving $MS$ from a better configuration is larger than the marginal search cost $MC$. It can be expected that $MC$ is an exponentially increasing function (as exampled in Table 1) while $MS$ is a decreasing function, as shown in Fig. 4(b). Therefore, the firm's



(a) (b)

**Fig. 4.** (a) The cost of sub-optimality is the difference between $c_t$ and $c_T$. (b) The firm's utility from the entire search is bounded below by $MS - MC > 0$



(a) (b)

**Fig. 5.** (a) the effect of problem size on the search outcome quality with the same search effort; (b) the effect of problem size on the search cost with the same outcome quality

utility from the entire search is bounded below by $MS - MC > 0$, but the searching is sub-optimal. If new search technology is developed to reduce the search cost, the curve *MC* will move to *MC'*, which will encourage firms to increase search efforts, and thus promote greater economic effi-ciency. If the size of networked supply chain *N* is increased, the curve *MC* will move to *MC"*, the firms will decrease their search efforts, leading to decrease in economic efficiency. On the other hand, e-business technologies have the potential to impact the way that transactions are conducted, and as a result, to reduce significantly the transaction costs in market, which will lead the curve *MS* move to *MS'*.

Now let us use the TSP to examine the effect of the problem size on the search behavior. The quality of search outcome depends not only on the search effort, but also on the problem size. To see how the problem size affects the search outcome, we run 10000 iterations on each of the five TSP instances, and then calculate the correlation dimension $D_c$ on the last 1000 iterations for each case respectively. The correlation dimension technique is popular diagnostic tool in the analysis of a dynamical process. In the TSP and heuristics context, the correlation dimension decreases as the search trajectory approaches a local optimum (Li, 2005). Fig. 5(a) illustrates the effect of problem size on the search outcome. We can see that, if we spend the same search effort (e.g. 10000 iterations) on each instance, the correlation dimension increases as the problem size increases, indicating decreasing quality of search outcome. Fig. 5(b) examines the same issue from different angle: if we want to obtain the same quality of search outcome (e.g. achieving $D_c \approx 1.56$ for the last 1000 search points) for all five instances, how much search time we must spend on each case? From the chart, we can see that, for 1000-city, 10000 iterations is needed to make the last 1000 search points reach $D_c \approx 1.56$. When the problem size increase to 2000 cities, we would have to spend 86000 iterations to make the last 1000 points reach $D_c \approx 1.56$. If we increase the problem size from 1000 to 5000 cities (an increase of 4 times), we have to increase the search effort 387 times (e.g. 3874000 iterations) to obtain the same quality of search outcome. These results indicate that search effort $t$ is increased according to a power law as the problem size $N$ increase:

$$t \propto N^d$$

This power law states that search effort $t$ changes as if it is the $d$ power of $N$.

These results are precisely analogous to the effect of the size of the networked supply chain on firms' search behavior. This suggests that the search cost of looking for optimal transaction stream configuration in a networked supply chain will increase at lease a power of the number of participants in the network. When more firms are involved in the networked supply chain, managers should consider investing much more efforts in the search process. Otherwise, their transaction stream configurations would be less optimal.

The computational complexity of NSCP can have a significant impact on market equilibrium and allocational efficiency, as illustrated in Fig. 6. The major impact of the computational complexity is that it typically increases the search cost firms must pay to obtain a better transaction stream configuration. Economic theory suggests that this increase in search costs plays a major role in determining the implication of networked supply chain in the market efficiency and equilibrium. If the firms spends more effort to obtain better transaction stream configurations, the overall lower transaction cost brought by the better configurations will cause the supply curve $S$ move to $S'$, leading to increase in quantity ($Q' - Q$) exchanged in the market. But the related search cost will causes the supply curve $S$ move to $S''$, leading to decrease in quantity ($Q - Q''$) exchanged and decreased allocational efficiency. These two forces are simultaneously increasing and decreasing quantity exchanged in the market. The computational complexity results in direct efficiency loss from increased search cost and in indirect but possibly larger loss in allocational efficiency from less optimal configurations. It is becoming clear that the complexity of networked supply chain will cause economic inefficiency and less market welfare and restrain economic growth. Internet-based electronic market may never live up to the promise of promoting frictionless market because this market can not be friction-free and economic forces may not perfectly due to the complexity.

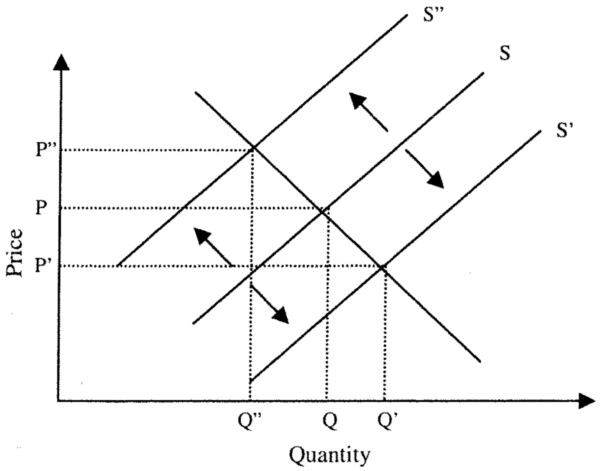


**Fig. 6.** The effect of search effort on the market

Another fundamental question will be raised in strategic management: what is the role of the complexity in the governance choice of the firm? Today, firms are faced with a myriad of organizational and market choices to organize supply chain activities that define how raw materials, information, and labor are used to produce products and services for business customers and consumers. Firms can use information technologies to help manage the risks and cost of performing interorganizational transactions and ensuring interorganizational coordination and control of those transactions. A collection of highly specialized independent firms can work together to perform, coordinate, and control supply chain activities.

When a firm faces process inefficiency, it may choose less hierarchical governance to avoid such type of inefficiency by reducing its business units and outsourcing one or more selective activities to external parties. In this case, the firm is moving towards market governance (Fig. 7). However, the complexity of networked

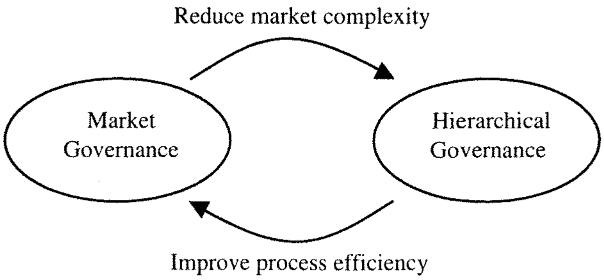


**Fig. 7.** Market governance vs. hierarchical governance in networked supply chain

supply chain may increase the search cost for more efficient market transaction. As the complexity increases, a firm will prefer more hierarchical governance in order to reduce this type of complexity. Firms eventually fall in some point between the market governance and hierarchical governance, which is the result of a firm's compromise between process efficiency and market complexity.

## 5. CONCLUSIONS

In this study, we have assumed a simple TSP model in order to gain insight about the effect of the complexity of networked supply chain on the search cost, recognizing that real-world networked supply chain is much more complicated. Of course, the TSP model is not the best choice to represent the NSCP. Further research is needed to find an appropriate choice (or if necessary the construction) of a suitable representative of the NSCP. Our analysis, nevertheless, shows that with such increase in the number of participants in a networked supply chain, searching for optimal transaction stream configuration becomes a combinatorial optimization problem and thus the computational complexity of the problem becomes *NP*-complete. The most important consequence of this complexity is that the best resource arrangements cannot be obtained by firms in an efficient manner and the best price cannot be obtained by consumers in the market. The complexity leads to an increase in search cost, which may partially or completely offset the decrease in transaction cost brought by advanced information technologies.

From technical standpoint, the search cost, although apparently small for Internet searches, can be substantial if an extensive computational search is performed. The bandwidth requirements of a *NP*-complete search may have no bounds. If many firms start looking for the optimal transaction stream configurations simultaneously, we may soon see a collapse of the current computing infrastructure. On the other hand, with the growth of electronic market, the networked supply chain becomes more and more complex. When information technology cannot keep pace with business demands for supporting the higher levels of the supply chain optimization effort, the electronic markets will fail to deliver on the promises.

Networked supply chain is becoming a means of achieving greater efficiency in almost every sphere of economic activity. With increased pressure from consumers, firms can no longer afford to operate linear, "one size fits all" supply chains. They need to radically change the nature of their supply chain operations to become truly consumer-driven. With product development and marketing costs rising constantly, the supply chain must become more dynamic, flexible and cost-efficient (Hawker *et al.*, 2004). Firms are currently investing billions of dollars to transform existing supply chains into consumer-driven supply chain networks. The emerging scholarly research in this field becomes focusing on the fundamentals of networked supply chain: designing market mechanisms, understanding firms' behavior in the networked supply chain, and the modeling of combinatorial markets. Recently, there has been a great deal of researches on various aspects of networked supply chain, with a heavy emphasis on supply chain design, in an attempt to develop new type of supply chain model that provides better economic outcomes through centralized computational decision making, low communication and coordination, quality by design, and scientific manufacturing. However, the computational complexity of networked supply chain presented in this study should be recognized when designing supply chain mechanism and studying firm's search behavior in the networked supply chain. The design and structure of networked supply chain is therefore shaped by the trade-off between search cost and market efficiency. In addition, the networked supply chain exhibit a level of computational complexity that requires algorithmic expertise, making it difficult to attack these design problems from a purely economic standpoint. This close interaction between computational and economic factors gives rise to one of the richest fields of interdisciplinary research (Anandalingam *et al.*, 2005). Furthermore, the Internet is forging an environment in which such complexity is increasing, not decreasing. Companies, individuals, and governments will have to decide on what is the best way to handle this emerging complexity.

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