Supernetworks: Paradoxes, Challenges, and New Opportunities

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Abstract

This paper discusses the realities of networks in a myriad of forms in the Information Age today and identifies paradoxes, as well as challenges and new opportunities surrounding their understanding, application, and management thereof.

1. Background

Throughout history, networks have served as the foundation for connecting humans to one another and their activities. Roads were laid, bridges built, and waterways crossed, so that humans, be they on foot, on animal, or vehicle could traverse physical distance. The airways were ultimately conquered through flight. Humans, separated by physical distance, communicated with one another, in turn, using the available means of the period, from smoke signals, drum boats, and pigeons, to the telegraph, telephone, and computer networks of today.

Today network systems provide the infrastructure and foundation for the functioning of our societies and economies. They come in many forms and include physical networks such as: transportation and logistical networks, communication networks, energy and power networks, as well as more *abstract* networks comprising: economic and financial networks, environmental networks, social, and knowledge networks.

For example, transportation networks give us the means to cross physical distance in order to conduct our daily activities. They provide us with access to both food as well as to consumer products and come in a myriad of forms: road, air, rail, or waterway. According to the U. S. Department of Transportation, the significance of transportation in dollar value alone as spent by US consumers, businesses, and governments was $950 billion in 1998.

Communication networks, in turn, allow us to communicate with friends and colleagues and to conduct the necessary transactions of life. They, through such innovations as the Internet, have transformed the manner in which we live, work, and conduct business today. Communication networks allow the transmission of voice, data/information, and/or video and can involve telephones, computers, as well as satellites, and microwaves. The trade publication *Purchasing* reports that corporate buyers alone spent $517.6 billion on telecommunications goods and services in 1999.

Energy networks, in addition, are essential to the very existence of the *Network Economy* and help to fuel not only transportation networks but in many settings also communication networks. They provide electricity to run the computers and to light our businesses, oil and gas to heat our homes and to power vehicles, and water for our very survival. In 1995, according to the U. S. Department of Commerce, the energy expenditures in the United States were \$515.8 billion.

Financial networks supply businesses with the resources to expand, to innovate, and to satisfy the needs of consumers. They allow individuals to invest and to save for the future for themselves and for their children and for governments to provide for their citizens and to develop and enhance communities.

Information technology has transformed the ways in which individuals work, travel, and conduct their daily activities, with profound implications for existing and future networks. Moreover, the *decision-making process* itself has been altered due to the addition of alternatives and options which were not, heretofore, possible or even feasible. The boundaries for decision-making have been redrawn as individuals can now work from home or purchase products from work. Indeed, we now live in an era in which the freedom to choose is weighted by the immensity of the number of choices and possibilities: Where should one live? Where should one work? And when? How should one travel? Or communicate? And with whom? Where should one shop? And how?

Managers can now locate raw materials and other inputs from suppliers through information networks in order to maximize profits while simultaneously ensuring timely delivery of finished goods. Financing for their businesses can be obtained online. Individuals, in turn, can obtain information about products from their homes and make their purchasing decisions accordingly. How should businesses avail themselves of new opportunities made possible through information technology? What kind of supply chain network structures will allow for greater productivity, efficiencies? How can firms more effectively compete and when and with whom should they cooperate? Finally, what are the ramifications of the decisions made in the new networked economy for the environment and its sustainability?

The reality of today's networks include: large-scale nature and complexity, increasing congestion, alternative behaviors of users of the networks, as well as interactions between the networks themselves, notably, between transportation and telecommunication networks. Indeed, recent historical events have dramatically and graphically illustrated the interconnectedness, interdependence, and vulnerability of organizations, business, and other enterprises on one another and on such critical network infrastructure systems as transportation and telecommunications. The decisions made by the users of the networks, in turn, affect not only the users themselves but others, as well, in terms of profits and costs, timeliness of deliveries, the quality of the environment, etc.

In this essay, we argue that new paradigms are needed to capture the complexities of decision-making in the Information Age. In particular, we believe that the concept of *supernetworks* is sufficiently general and yet elegantly compact to formalize such decision-making. "Super" networks are networks that are "above and beyond" existing networks, which consist of nodes, links, and flows, with nodes corresponding to locations in space, links to connections in the form of roads, cables, etc., and flows to vehicles, data, etc. Supernetworks are conceptual in scope, graphical in perspective, and, with the accompanying theory, predictive in nature.

In particular, the supernetwork framework, captures, in a unified fashion, decision-making facing a variety of economic agents including consumers and producers as well as distinct intermediaries in the context of today's networked economy. The decision-making process may entail weighting trade-offs associated with the use of transportation versus telecommunication networks. The behavior of the individual decision-makers is modeled as well as their interactions on the complex network systems with the goal of identifying the resulting flows and prices. The origins of supernetworks can be traced to the study of transportation networks, telecommunication networks, as well as economic and financial networks, and, interestingly, to biology. Here we take the synthetic approach promulgated by Nagurney and Dong (2002). In Figure 1, we provide a conceptualization of supernetworks that emphasizes the interdependence of distinct network systems.

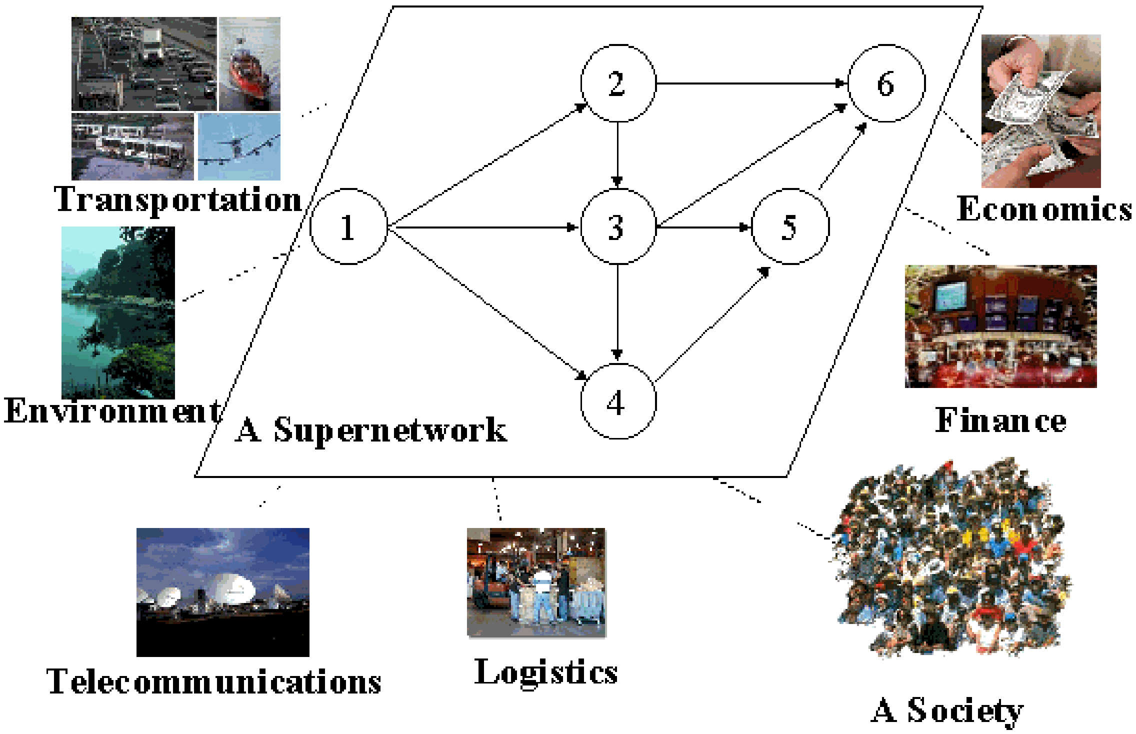

Figure 1: Conceptualization of a Supernetwork

Table 1: Examples of Classical Networks

Network System	**Nodes**	**Links**	**Flows**
Transportation			
Urban	Intersections, Homes, Places of Work	Roads	Autos
Air	Airports	Airline Routes	Planes
Rail	Railyards	Railroad Track	Trains
Manufacturing and Logistics	Distribution Points, Processing Points	Routes Assembly Line	Parts, Products
Communication	Computers	Cables	Messages
	Satellites	Radio	Messages
	Phone Exchanges	Cables, Microwaves	Voice, Video
Energy	Pumping Stations	Pipelines	Water
	Plants	Pipelines	Gas, Oil

2. Classical Networks

For definiteness, we first present in Table 1 some basic *classical* networks and the associated nodes, links, and flows. By *classical* network is meant a network in which the nodes correspond to physical locations in space and the links to physical connections between the nodes.

We note that the topic of networks and the management thereof dates to ancient times with examples including the publicly provided Roman road network and the "time of day" chariot policy, whereby chariots were banned from the ancient city of Rome at particular times of day (cf. Banister and Button (1993)). The formal study of networks, consisting of *nodes, links, and flows*, in turn, involves: how to model such applications (as well as numerous other ones) as mathematical entities, how to study the models qualitatively, how to design algorithms to solve the resulting models effectively to enable the ultimate prediction of the underlying variables, and, finally, how to design appropriate policy instruments. The study of networks is necessarily *interdisciplinary* in nature due to their breadth of appearance and is based on techniques from applied mathematics, computer science, and engineering with applications as varied as finance and even biology. Network models and tools are widely used by businesses, industries, as well as governments today (cf. Ahuja, Magnanti, and Orlin (1993), Nagurney and Siokos (1997), Nagurney (1999, 2000a), and the references therein).

Basic examples of network problems are: *the shortest path problem*, in which one seeks to determine the most efficient path from an origin node to a destination node; *the maximum flow problem*, in which one wishes to determine the maximum flow that one can send from an origin node to a destination node, given that there are capacities on the links that cannot be exceeded, and *the minimum cost flow problem*, where there are both costs and capacities associated with the links and one must satisfy the demands at the destination nodes, given supplies at the origin nodes, at minimal total cost associated with shipping the flows, and subject to not exceeding the arc capacities. Applications of the shortest path problem are found in transportation and telecommunications, whereas the maximum flow problem arises in machine scheduling and network reliability settings, with applications of the minimum cost flow problem ranging from warehousing and distribution to vehicle fleet planning and scheduling.

Networks also appear in surprising and fascinating ways for problems, which initially may not appear to involve networks at all, such as a variety of financial problems and in knowledge production and dissemination. Hence, the study of networks is not limited to only physical networks where nodes coincide with locations in space but applies also to abstract networks. The ability to harness the power of a network formalism provides a competitive advantage since:

- many present-day problems are concerned with flows be they, material, human, capital, or informational over space and time and, hence, ideally suited as an application domain for network theory;

- one may avail oneself of a graphical or visual depiction of different problems;

- one may identify similarities and differences in distinct problems through their underlying network structure, and

- one may apply efficient network algorithms for problem solution to predict the vehicular, commodity, financial, and informational flows.

3. The Realities of Today's Networks

The characteristics of today's networks include: large-scale nature and complexity of network topology; congestion; alternative behavior of users of the network, which may lead to paradoxical phenomena, and the interactions among networks themselves such as in transportation versus telecommunications networks. Moreover, policies surrounding networks today may have a major impact not only economically but also socially.

Large-Scale Nature and Complexity

Many of today's networks are characterized by both a large-scale nature and complexity of the underlying network topology. For example, in Chicago's Regional Transportation Network, there are 12,982 nodes, 39,018 links, and 2,297,945 origin/destination (O/D) pairs (see Bar-Gera (1999)), whereas in the Southern California Association of Governments model there are 3,217 origins and/or destinations, 25,428 nodes, and 99,240 links, plus 6 distinct classes of users (cf. Wu, Florian, and He (2000)).

In terms of the size of existing telecommunications networks, AT&T's domestic network has 100,000 origin/destination pairs (cf. Resende (2000)), whereas in their detail graph applications in which nodes are phone numbers and edges are calls, there are 300 million nodes and 4 billion edges (cf. Abello, Pardalos, and Resende (1999)).

Congestion

Congestion is playing an increasing role in not only transportation networks but also in telecommunication networks. For example, in the case of transportation networks in the United States alone, congestion results in $100 billion in lost productivity, whereas the figure in Europe is estimated to be $150 billion. The number of cars is expected to increase by 50% by 2010 and to double by 2030 (see Nagurney (2000a)).

In terms of the Internet, with over 275 million present users, the Federal Communications Commission reports that the volume of traffic is doubling every 100 days, which is remarkable given that telephone traffic has typically increased only by about 5 percent a year (cf. Labaton (2000)). As individuals increasingly access the Internet through wireless communication such as through handheld computers and cellular phones, experts fear that the heavy use of airwaves will create additional bottlenecks and congestion that could impede the further development of the technology.

System-Optimization versus User-Optimization and the Braess Paradox

In many of today's networks, not only is congestion a characteristic feature leading to nonlinearities, but the behavior of the users of the networks themselves may be that of noncooperation. For example, in the case of urban transportation networks, travelers select their routes of travel from an origin to a destination so as to minimize their own travel cost or travel time, which although "optimal" from an individual's perspective (user-optimization) may not be optimal from a societal one (system-optimization) where one has control over the flows on the network and, in contrast, seeks to minimize the total cost in the network and, hence, the total loss of productivity (see, e.g., Wardrop (1952), Beckmann, McGuire, and Winsten (1956), Dafermos and Sparrow (1969), and Nagurney (1999)). Consequently, in making any kind of policy decisions in such networks one must take into consideration the users of the particular network. Indeed, this point is vividly illustrated through a famous example known as the Braess paradox, in which it is assumed that the underlying behavioral principle is that of user-optimization. In the Braess (1968) network, the addition of a new road with no change in the travel demand results in all travelers in the network incurring a higher travel cost and, hence, being worse off!

The increase in travel cost on the paths is due, in part, to the fact that in this network two links are shared by distinct paths and these links incur an increase in flow and associated cost. Hence, Braess's paradox is related to the underlying topology of the networks. One may show, however, that the addition of a path connecting an O/D pair that shares no links with the original O/D pair will never result in Braess's paradox for that O/D pair.

Interestingly, as reported in the *New York Times* by Kolata (1990), this phenomenon has been observed in practice both in the case of New York City when in 1990, 42nd Street was closed for Earth Day and the traffic flow actually improved. Just to demonstrate that it is not a purely New York or US phenomena concerning drivers and their behavior an analogous situation was observed in Stuttgart where a new road was added to the downtown but the traffic flow worsened and following complaints, the new road was torn down (see Bass (1992)).

This phenomenon is also relevant to telecommunications networks (see Korilis, Lazar, and Orda (1999)) and, in particular, to the Internet which is another example of a "noncooperative network" and, therefore, network tools have wide application in this setting as well especially in terms of congestion management and network design (see also Cohen and Kelly (1990)).

Network Interactions

Clearly, one of the principal facets of the Network Economy is the interaction among the networks themselves. For example, the increasing use of electronic commerce especially in business to business transactions is changing not only the utilization and structure of the underlying logistical networks but is also revolutionizing how business itself is transacted and the structure of firms and industries. Cellular phones are being using as vehicles move dynamically over transportation networks resulting in dynamic evolutions of the topologies themselves. The unifying concept of supernetworks with associated methodologies allows one to explore the interactions among such networks as transportation networks, telecommunication networks, as well as financial networks.

More Paradoxes: Transportation and Telecommunications versus the Environment

The demand for transportation on the one hand with a growing realization of the associated negative externalities due, for example, to congestion and pollution are raising questions of sustainability of the transportation infrastructure. For example, 15% of the world's emissions of carbon dioxide are due to motor vehicles, as are 50% of the emissions of nitrogen oxide, and 90% of the carbon monoxide. The necessity of identifying the behavior of the users of such networks coupled with the interactions between transportation and environmental networks is vividly illustrated through several transportation/environmental paradoxes identified by Nagurney (2000a, b). For example, the addition of a new link (road) to a transportation network may result in an increase in vehicular emissions with no change

Table 2: Examples of Supernetwork Applications

Telecommuting/Commuting Decision-Making
Teleshopping/Shopping Decision-Making
Supply Chain Networks with Electronic Commerce
Financial Networks with Electronic Transactions

in travel demand; a decrease in travel demand associated with a particular origin/destination pair of nodes of travel may result in an increase in emissions, and a reallocation of travelers from a mode of higher emissions to that of one with lower emissions may actually result in an increase in total emissions!

Recently, Nagurney and Dong (2001) identified paradoxes in networks with zero emission links such as telecommmunication networks. In particular, they showed through simple examples how the addition of a zero emission link may result in an increase in total emissions with no change in demand and how a decrease in demand on a network with a zero emission link may result in an increase in total emissions. Hence, one must incorporate the network topology, the relevant cost and demand structure as well as the behavior of the users of the particular transportation/telecommunication network into any policy aimed at pollution abatement! These paradoxes further illustrate the interconnectivity among distinct network systems and that they cannot be studied simply in isolation.

4. Supernetworks and Applications

Supernetworks may be comprised of such networks as transportation, telecommunication, logistical and financial networks, among others. They may be *multilevel* as when they formalize the study of supply chain networks or *multitiered* as in the case of financial networks with intermediation. Furthermore, decision-makers on supernetworks may be faced with multiple criteria and, hence, the study of supernetworks also includes the study of multicriteria decision-making. In Table 2, some specific applications of supernetworks are given, upon which we elaborate below.

In particular, the supernetwork framework allows one to formalize the alternatives available to decision-makers, to model their individual behavior, typically, characterized by particular criteria which they wish to optimize, and to, ultimately, compute the flows on the supernetwork, which may consist of product shipments, travelers between origins and destinations, financial flows, as well as the associated "prices." Hence, the concern is with *human decision-making* and how the supernetwork concept can be utilized to crystallize and inform in this dimension.

4.1 Telecommuting versus Commuting Decision-Making

According to Hu and Young (1996), person-trips and person-miles of commuting increased between 1990 and 1995, both in absolute terms and as a share of all personal travel. Constituting 18% of all person-trips and 22% of all person-miles in 1995, commuting is the single most common trip purpose. Furthermore, as argued by Mokhtarian (1998) (see also Mokhtarian (1991)), it is very likely that a greater proportion of commute trips rather than other types of trips will be amenable to substitution through telecommunications. Consequently, telecommuting most likely has the highest potential for travel reduction of any of the telecommunication applications. Therefore, the study of telecommuting and its impacts is a subject worthy of continued interest and research. Furthermore, recent legislation that allows federal employees to select telecommuting as an option (see United States (2000)), underscores the practical importance of this topic.

The decision-makers in the context of this application are travelers, who seek to determine their *optimal* routes of travel from their origins, which are residences, to their destinations, which are their places of work. Note that, in the supernetwork framework, a link may correspond to an actual physical link of transportation or an abstract or virtual link corresponding to a telecommuting link. Furthermore, the supernetwork representing the problem under study can be as general as necessary and a path may consist of a set of links corresponding to physical and virtual transportation choices such as would occur if a worker were to commute to a work center from which she could then telecommute. In Figure 2, a conceptualization of this idea is provided.

Observe that, in Figure 2, nodes 1 and 2 represent locations of residences, whereas node 6 denotes the place of work. Work centers from which workers can telecommute are located

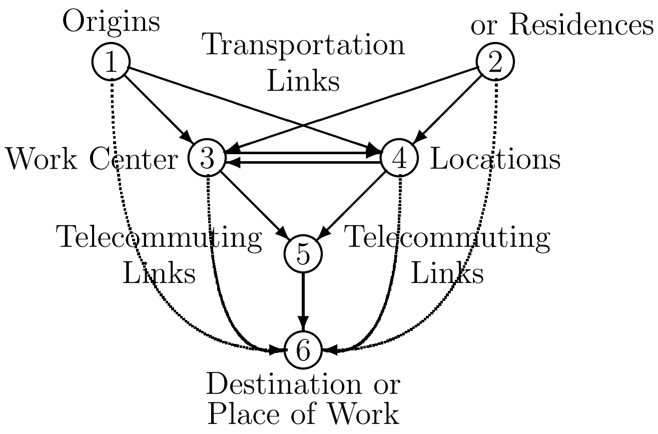

Figure 2: A Supernetwork Conceptualization of Commuting versus Telecommuting

at nodes 3 and 4 which also serve as intermediate nodes for transportation routes to work. The links: $(1, 6)$, $(3, 6)$, $(4, 6)$, and $(2, 6)$ are telecommunication links depicting virtual transportation to work via telecommuting, whereas all other links are physical links associated with commuting. Hence, the paths $(1, 6)$ and $(2, 6)$ consisting, respectively, of the individual single links represent "going to work" virtually whereas the paths consisting of the links: $(1, 3)$, $(3, 6)$ and $(2, 4)$, $(4, 6)$ represent first commuting to the work centers located at nodes 3 and 4, from which the workers then telecommute. Finally, the remaining paths represent the commuting options for the residents at nodes 1 and 2. The conventional travel paths from node 1 to node 6 are as follows: (1,3), (3,5), (5,6); (1,3), (3,4), (4,5), (5,6); (1,4), (4,5), (5,6), and (1,4), (4,3), (3,5), (5,6). Note that there may be as many classes of users of this network as there are groups who perceive the tradeoffs among the criteria in a similar fashion.

Of course, the network depicted in Figure 2 is illustrative, and the actual network can be much more complex with numerous paths depicting the physical transportation choices from one's residence to one's work location. Similarly, one can further complexify the telecommunication link/path options. Also, we emphasize, that a *path* within this framework is sufficiently general to also capture a choice of mode, which, in the case of transportation, could correspond to busses, trains, or subways (that is, public transit) and, of course, to the use of cars (i.e., private vehicles). Similarly, the concept of path can be used to represent a distinct telecommunications option.

In this framework, since the decision-makers are travelers, the path flows and link flows by class would correspond, respectively, to the number of travelers of the class selecting a particular path and link.

We now turn to a discussion of the criteria, which one can expect to be reasonable in the context of decision-making in this particular application. The first multicriteria traffic network models, due to Schneider (1968) and Quandt (1967), considered two criteria and these were travel time and travel cost. Of course, telecommuting was not truly an option in those days. Dafermos (1981), Leurent (1993), Marcotte (1998), as well as Nagurney (2000d) also considered those two criteria but handled congestion on the networks as well. Nagurney, Dong, and Mokhtarian (2000), in turn, focused on the development of an integrated multicriteria network equilibrium model, which was the first to consider telecommuting versus commuting tradeoffs. They considered three criteria: travel time, travel cost, and an opportunity cost to trade-off the opportunity cost associated with not being physically able to interact with colleagues. Further developments, including the incorporation of additional decision-making criteria, including safety and discussion of the associated analytical methodologies, can be found in Nagurney and Dong (2002), and in Nagurney, Dong, and Mokhtarian (2002).

The behavioral assumption is that travelers of a particular class are assumed to choose the paths associated with their origin/destination (O/D) pair so that the generalized cost on that path, which consists of a weighting of the different criteria (which can be different for each class of decision-maker and can also be link-dependent), is minimal. An equilibrium is assumed to be reached when the multicriteria network equilibrium conditions are satisfied whereby only those paths connecting an O/D pair are utilized such that the generalized costs on the paths, as perceived by a class, are equal and minimal.

4.2 Modeling Teleshopping versus Shopping Decision-Making

Here a multicriteria network equilibrium model for teleshopping versus shopping is described. The model generalizes the model proposed in Nagurney, Dong, and Mokhtarian (2001). For further details, including numerical examples, see Nagurney and Dong (2002).

Although there is now a growing body of transportation literature on telecommuting (cf. Mokhtarian (1998)), the topic of teleshopping, which is a newer concept, has received less attention to date. In particular, shopping refers to a set of activities in which consumers seek and obtain information about products and/or services, conduct a transaction transferring ownership or right to use, and spatially relocate the product or service to the new owner (Mokhtarian and Salomon (2002)). Teleshopping, in turn, refers to a case in which one or more of those activities is conducted through the use of telecommunication technologies. Today, much attention is focused on the Internet as the technology of interest, and Internet-based shopping is, indeed, increasing. In this setting, teleshopping represents the consumer's role in B2C electronic commerce. Although the model is in the context of Internet-based shopping, the model can apply more broadly.

Note that outside the work of Nagurney, Dong, and Mokhtarian (2001, 2002), there has been essentially no study of the transportation impacts of teleshopping beyond speculation (e.g., Gould (1998), Mokhtarian and Salomon (2002)).

Assume that consumers are engaged in the purchase of a product which they do so in a repetitive fashion, say, on a weekly basis. The product may consist of a single good, such as a book, or a bundle of goods, such as food. Assume also that there are locations, both virtual and physical, where the consumers can obtain information about the product. The virtual locations are accessed through telecommunications via the Internet whereas the physical locations represent more classical shopping venues such as stores and require physical travel to reach.

The consumers may order/purchase the product, once they have selected the appropriate location, be it virtual or physical, with the former requiring shipment to the consumers' locations and the latter requiring, after the physical purchase, transportation of the consumer with the product to its final destination (which we expect, typically, to be his residence or, perhaps, place of work).

Refer to the network conceptualization of the problem given in Figure 3. We now identify the above concepts with the corresponding network component. The idea of such a shopping network was first proposed by Nagurney, Dong, and Mokhtarian (2001).

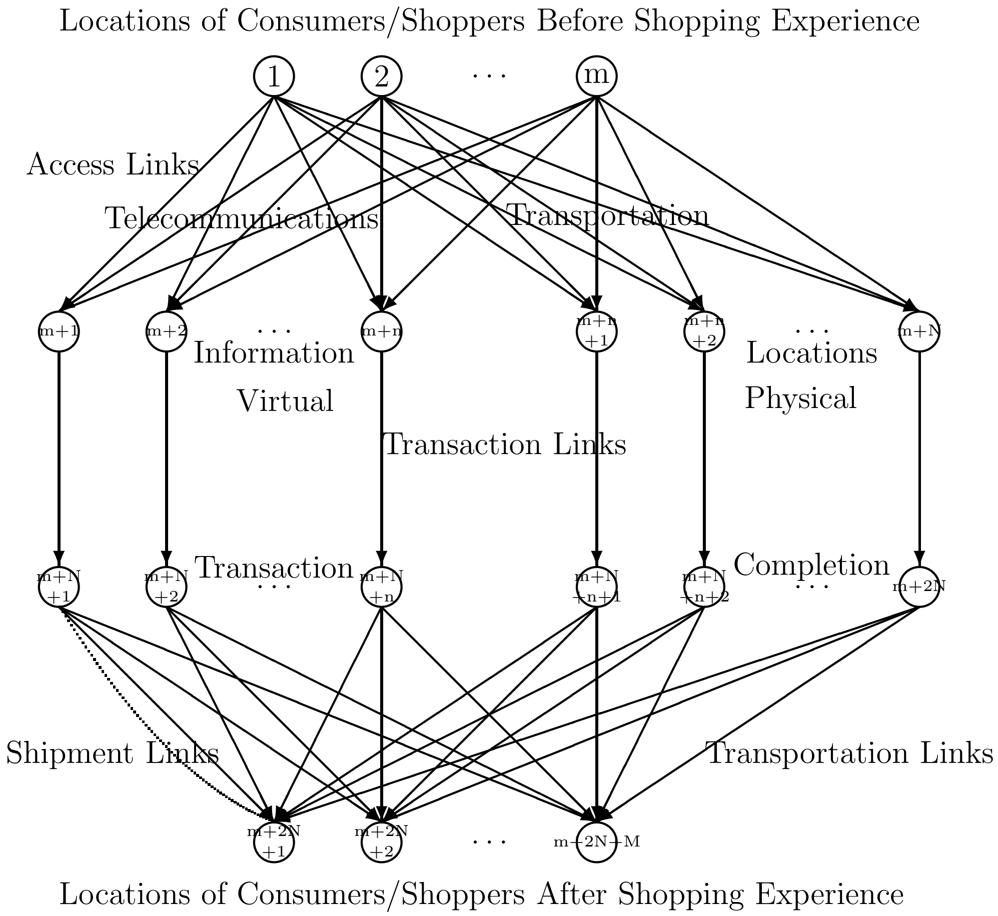

Figure 3: A Supernetwork Framework for Teleshopping versus Shopping

Observe that the network depicted in Figure 3 consists of four levels of nodes with the first (top) level and the last (bottom) level corresponding to the locations (destinations) of the consumers involved in the purchase of the product. We emphasize that each location may have many consumers. The second level of nodes, in turn, corresponds to the information locations (and where the transactions also take place), with the first set of such nodes representing the virtual or Internet-based locations and the second such set denoting the physical locations of information corresponding to stores, for example. The third level of nodes corresponds to the completion of the transaction with the first set of such nodes corresponding to Internet sites where the product could have been purchased (and where it has been assumed that information has also been made available in the previous level of nodes) and the second set of such nodes corresponding to the completion of the transaction at the physical stores.

We now discuss the links connecting the nodes in the network in Figure 3. A link connecting a top level node (consumers' location) to an information node at the second level corresponds to an *access* link for information. The links terminating in the first set of nodes of the second level correspond to telecommunication access links, whereas those terminating in the second set of nodes correspond to (aggregated) transportation links.

As can be seen from Figure 5, from each second tier node there emanates a link, which corresponds to a completion of a transaction node. The first set of such links correspond to virtual orders, whereas the subsequent links denote physical orders/purchases. Finally, there are links emanating from the transaction nodes to the consumers' (final) destination nodes, with the links emanating from the first set of transaction nodes denoting shipment links (since the product, once ordered, must be shipped to the consumer), and the links from the second set representing physical transportation links to the consumers' destinations. Note that, in the case of the latter links, the consumers (after purchasing the product) transport it with themselves, whereas in the former case, the product is shipped to the consumers. Observe that in the supernetwork framework, we explicitly allow for alternative modes of shipping the product which is represented by an additional link (or links) connecting a virtual transaction node with the consumers' location.

The above network construction captures the *electronic dissemination* of goods (such as books or music, for example) in that an alternative shipment link in the bottom tier of links may correspond to the virtual or electronic shipment of the product.

An origin/destination pair in this network corresponds to a pair of nodes from the top tier in Figure 5 to the bottom tier. In the shopping network framework, a path consists of a sequence of choices made by a consumer. For example, the path consisting of the links: $(1, m+1), (m+1, m+N+1), (m+N+1, m+2N+1)$ would correspond to consumers located at location 1 accessing virtual location $m+1$ through telecommunications, placing an order at the site for the product, and having it shipped to them. The path consisting of the links: $(m, m+N)$, $(m+N, m+2N)$, and $(m+2N, m+2N+M)$, on the other hand, could reflect that consumers at location m (which could be a work location or home) drove to the store at location $m+N$, obtained the information there concerning the product, completed the transaction, and then drove to node M. Note that a path represents a sequence of possible options for the consumers. The flows, in turn, reflect *how many* consumers of a particular class actually select the particular paths and links, with a zero flow on a path corresponding to the situation that no consumer elects to choose that particular sequence of links.

The criteria that are relevant to decision-making in this application are: time, cost, opportunity cost, and safety or security risk, where, in contrast to the telecommuting application time need not be restricted simply to *travel* time and, depending on the associated link, may include transaction time. In addition, the cost is not exclusively a travel cost but depends on the associated link and can include the transaction cost as well as the product price, or shipment cost. Moreover, the opportunity cost now arises when shoppers on the Internet cannot have the physical experience of trying the good or the actual sociableness of the shopping experience itself. Finally, the safety or security risk cost now can reflect not only the danger of certain physical transportation links but also the potential of credit card fraud, etc.

For example, an article in *The Economist* (2001) notes that “websites are not much good for replicating the social functions of shopping” and that “consumers are often advised against giving their credit-card numbers freely over the Internet, and this remains one of the most-cited reasons for not buying things online.”

Assuming weights for each class, link, and criterion, a generalized link cost for each class and link can the be constructed as well as a generalized path cost for a class of consumer (cf. Nagurney and Dong (2002)). The behavioral assumption is that consumers of a particular class are assumed to choose the paths associated with an O/D pair so that their generalized path costs are minimal.

Using the methodologies discussed in Nagurney and Dong (2002) one can then solve the model and obtain the number of decision-makers who select the different options and the incurred generalized costs. One can then ascertain the relative popularity of the various options.

4.3 Supply Chain Networks

The study of supply chain network problems through modeling, analysis, and computation is a challenging topic due to the complexity of the relationships among the various decision-makers, such as suppliers, manufacturers, distributors, and retailers as well as the practical importance of the topic for the efficient movement of products. The topic is multidisciplinary by nature since it involves particulars of manufacturing, transportation and logistics, retailing/marketing, as well as economics.

The introduction of electronic commerce has unveiled new opportunities in terms of research and practice in supply chain analysis and management since electronic commerce (e-commerce) has had a huge effect on the manner in which businesses order goods and have them transported with the major portion of e-commerce transactions being in the form of business-to-business (B2B). Estimates of B2B electronic commerce range from approximately .1 trillion dollars to 1 trillion dollars in 1998 and with forecasts reaching as high as \$4.8 trillion dollars in 2003 in the United States (see Federal Highway Administration (2000), Southworth (2000)). It has been emphasized that the principal effect of business-to-business (B2B) commerce, estimated to be 90% of all e-commerce by value and volume, is in the creation of new and more profitable supply chain networks.

In Figure 4, we depict a four-tiered supply chain network in which the top tier consists of suppliers of inputs into the production processes used by the manufacturing firms (the second tier), who, in turn, transform the inputs into products which are then shipped to the third tier of decision-makers, the retailers, from whom the consumers can then obtain the

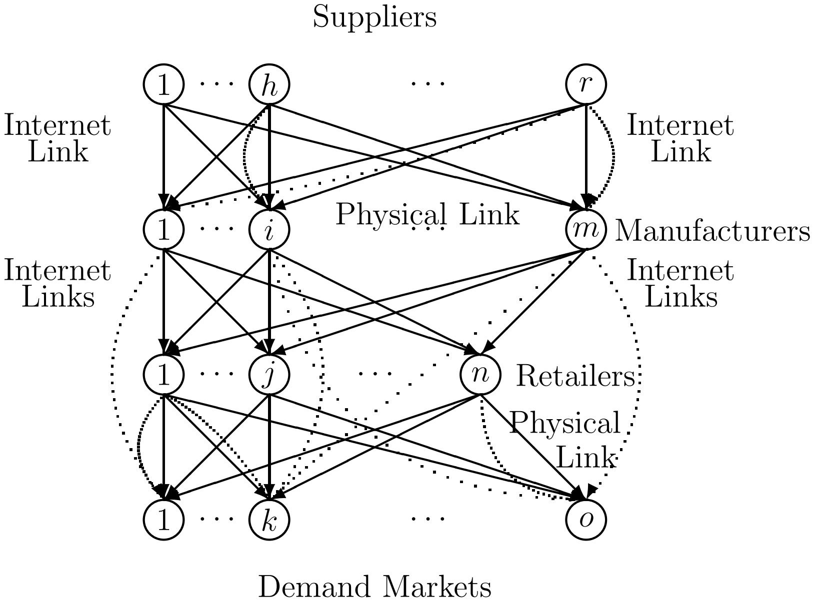

Figure 4: The Supernetwork Structure of the Supply Chain Network with Suppliers, Manufacturers, Retailers, and Demand Markets and Electronic Commerce

products. Here we allow not only for physical transactions to take place but also for virtual transactions, in the form of electronic transactions via the Internet to represent electronic commerce. In the supernetwork framework, both B2B and B2C can be considered, modeled, and analyzed. The decision-makers may compete independently across a given tier of nodes of the network and cooperate between tiers of nodes.

In particular, Nagurney, Loo, Dong, and Zhang (2002) have applied the supernetwork framework to supply chain networks with electronic commerce in order to predict product flows between tiers of decision-makers as well as the prices associated with the different tiers. They assumed that the manufacturers as well as the retailers are engaged in profit maximizing behavior whereas the consumers seek to minimize the costs associated with their purchases. The model therein determines the volumes of the products transacted electronically or physically.

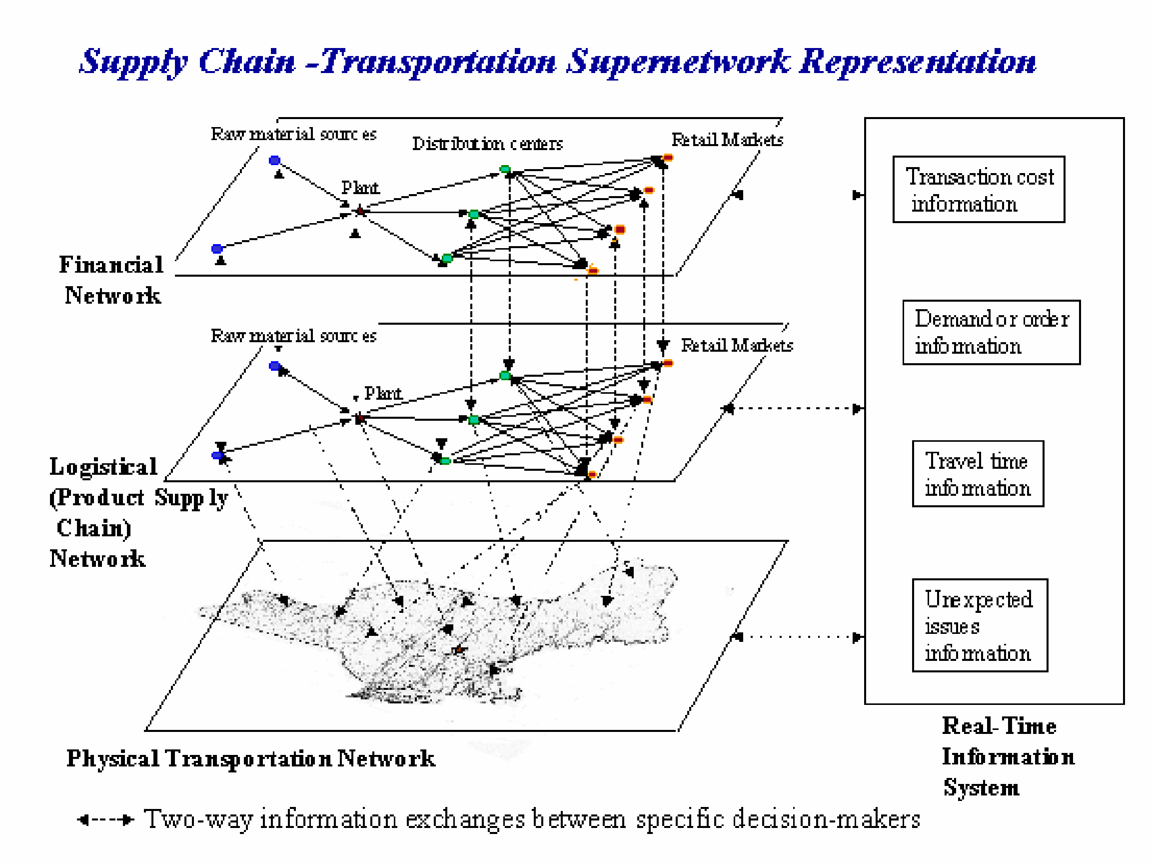

Figure 5: A Multilevel Supply Chain Supernetwork

As mentioned earlier, supernetworks may also be multilevel in structure. In particular, Nagurney, Ke, Cruz, Hancock, and Southworth (2002) demonstrated how supply chain networks can be depicted and studied as multilevel networks in order to identify not only the product shipments but also the financial flows as well as the informational ones. In Figure 5, we demonstrate how a supply chain can be depicted as a multilevel supernetwork in which the financial network as well as the actual physical transportation network are also represented.

For example, in the supernetwork depicted in Figure 5, the logistical network affects the flows on the actual transportation network whereas the financial flows are due to payments as they proceed up the chain and as the transactions are completed. The information flows, in turn, are in the form of demand, cost, and flow data at the instance in time.

Obviously, in the setting of supply chain networks and, in particular, in global supply chains, there may be much risk and uncertainty associated with the underlying functions. Some research along those lines in being undertaken (cf. Dong, Zhang, and Nagurney (2002), and Nagurney, Cruz, and Matsypura (2002)). Continuing efforts to include uncertainty and risk into modeling and computational efforts in a variety of supernetworks and their applications is of paramount importance given the present economic and political climate.

In addition, we emphasize that the inclusion of environmental variables and criteria is also an important topic for research and practice in the context of supply chain networks (cf. Nagurney and Fuminori (2002)). In particular, we note that additional effort needs to be extended on the topic of reverse logistics and the recycling of electronic wastes.

4.4 Financial Networks

Financial networks have been utilized in the study of financial systems since the work of Quesnay in 1758, who depicted the circular flow of funds in an economy as a network. His conceptualization of the funds as a network, which was abstract, is the first identifiable instance of a supernetwork. Quesnay's basic idea was subsequently applied in the construction of flow of funds accounts, which are a statistical description of the flows of money and credit in an economy (cf. Board of Governors (1980)). However, since the flow of funds accounts are in matrix form, and, hence, two-dimensional, they fail to capture the behavior on a micro level of the various financial agents/sectors in an economy, such as banks, households, insurance companies, etc. Moreover, the generality of the matrix tends to obscure certain structural aspects of the financial system that are of continuing interest in analysis, with the structural concepts of concern including those of financial intermediation.

Advances in telecommunications and, in particular, the adoption of the Internet by businesses, consumers, and financial institutions have had an enormous effect on financial services and the options available for financial transactions. Distribution channels have been transformed, new types of services and products introduced, and the role of financial intermediaries altered in the new economic networked landscape. Furthermore, the impact of such advances has not been limited to individual nations but, rather, through new linkages, has crossed national boundaries.

The topic of *electronic* finance has been a growing area of study (cf. Claessens, Glaessner, and Klingebiel (2000, 2001) and Allen, Hawkins, and Sato (2001), and the references therein), due to its increasing impact on financial markets and financial intermediation, as well as related regulatory issues and governance. Of particular emphasis has been the conceptualization of the major issues involved and the role of networks is the transformations (see McAndrews and Stefanidis (2000), Banks (2001), Allen, Hawkins, and Sato (2001), Economides (2001), and Nagurney and Dong (2002)).

Nevertheless, the complexity of the interactions among the distinct decision-makers involved, the supply chain aspects of the financial product accessibilities and deliveries, as well as the availability of physical as well as electronic options, and the role of intermediaries, have defied the construction of a unified, quantifiable framework in which one can assess the resulting financial flows and prices.

Here we briefly describe a supernetwork framework for the study of financial decision-making in the presence of intermediation and electronic transactions. Further details can be found in Nagurney and Ke (2001, 2002). The framework is sufficiently general to allow for the modeling, analysis, and computation of solutions to such problems.

The financial network model consists of: agents or decision-makers with sources of funds, financial intermediaries, as well as consumers associated with the demand markets. In the model, the sources of funds can transact directly electronically with the consumers through the Internet and can also conduct their financial transactions with the intermediaries either physically or electronically. The intermediaries, in turn, can transact with the consumers either physically in the standard manner or electronically. The depiction of the network at equilibrium is given in Figure 6.

It is assumed that the agents with sources of funds as well as the financial intermediaries seek to maximize their net revenue (in the presence of transaction costs) while, at the same time, minimizing the risk associated with the financial products. The solution of the model yields the financial flows between the tiers as well as the prices. Here we also allow for

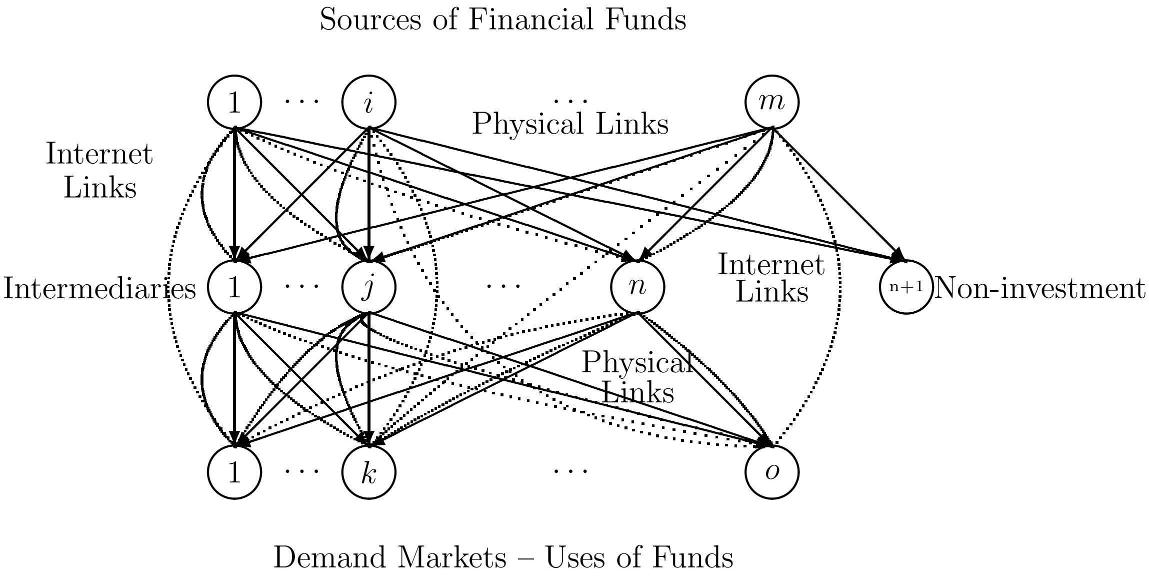

Figure 6: The Structure of the Financial Network with Electronic Transactions

the option of having the source agents not invest a part (or all) of their financial holdings. More recently, Nagurney and Cruz (2002) have demonstrated that the financial supernetwork framework can also be extended to model international financial networks with intermediation in which there are distinct agents in different countries and the financial products are available in different currencies.

5. Summary and Conclusions

In this paper, we have described the realities surrounding networks today and the challenges and complexities posed for their analysis and study. In particular, we have argued for new paradigms to capture decision-making in the Information Age. We have focused on the concept of *supernetworks* and have discussed a variety of applications that come under this umbrella ranging from telecommuting versus commuting decision-making to financial networks with electronic transactions and intermediation. In addition, we have emphasized possible new directions for research. The advances in information technologies have enabled not only new connections and applications but have, at the same time, allowed for the implementation of powerful analytical methodologies for the solution of complex network problems which underly our economies and societies today.

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