Supernetworks: The Paradigm for Critical Infrastructure and the Supernetworked Economy

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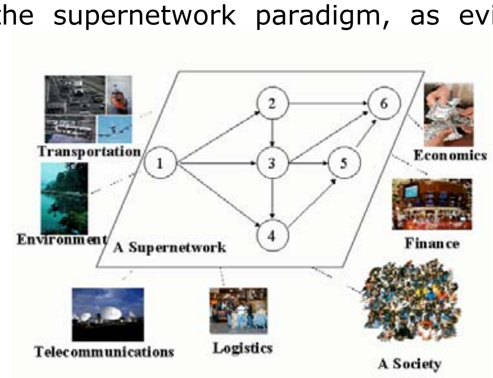
In an invited essay in *OR/MS Today*, June 2000, entitled, *Navigating the Network Economy* http://www.lionhrtpub.com/orms/orms-6-00/nagurney.html I argued that we were in a new era of *Supernetworks.* Since that time the world has been transformed through events of historical proportions which have dramatically and vividly reinforced the dependence of our societies and economies on critical infrastructure networks including *physical* networks; i.e., transportation and logistical networks, communication networks, energy and power networks, as well as more *abstract* networks comprising: financial networks, environmental networks, social, and knowledge networks, and *combinations* thereof. Indeed, recent historical events have graphically illustrated the interconnectedness, interdependence, and vulnerability of organizations, businesses, and other enterprises on critical network infrastructure systems. The decisions made by the users of the networks, in turn, affect not only the users themselves but others, as well, in terms of safety and security, profits and costs, timeliness of deliveries, the quality of the environment, etc. Hence, the understanding of the impacts of human decision-making on such networks is of paramount importance.

In this essay, I argue that Supernetworks are *the paradigm* for the modeling, analysis, and solution of critical infrastructure problems in the *Supernetworked Economy*. In particular, the supernetwork paradigm, as evidenced by the book



Supernetworks: Decision-Making for the Information Age, by Nagurney and Dong (2002), along with many articles and applications (see: http://supernet.som.umass.edu), is sufficiently general and yet elegantly compact to formalize and make a major impact on the design, robustness, and evolution of critical infrastructure networks, their usage, evaluation, and management thereof. In particular, **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, which is networked-based, predictive in nature.

The supernetwork framework, captures, in a unified fashion, decision-making facing a variety of decision-makers including consumers and producers as well as distinct intermediaries, such as financial brokers, electric power transmitters, and electronic retailers in the context of today's supernetworked 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. By being able to predict the various flows based on network topologies and interactions amongst the decision-makers one then gains deep insights into the vulnerabilities as well as the strengths of various linkages.

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, as reviewed in Nagurney and Dong (2002). Here I take that synthetic and rigorous approach. In the Figure below, I provide a conceptualization of supernetworks for critical infrastructure that emphasizes the interdependence of distinct network systems. Note that the image dates to 2001 which coincides with the establishment of the Virtual Center for Supernetworks.

Clearly, one of the principal facets of critical infrastructure networks 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 used as vehicles move dynamically over transportation networks resulting in dynamic evolutions of the topologies themselves. Power outages in one part of the world may affect transportation and financial systems around the globe as the August 14, 2003 blackout demonstrated. 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, to capture the dynamic interactions and also to measure the associated risks and gains/losses.

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 the Table below, some specific applications of supernetworks are given, which have been studied by myself with students and colleagues. Subsequently, I elaborate upon several of the applications. For various publications on these topics, see: http://supernet.som.umass.edu

Examples of Supernetwork Critical Infrastructure Applications
Telecommuting/Commuting Decision-Making
Teleshopping/Shopping Decision-Making
Supply Chain Networks with Electronic Commerce
Financial Networks with Electronic Transactions
Environmental and Energy Networks including E-Cycling Networks
Knowledge and Social Networks

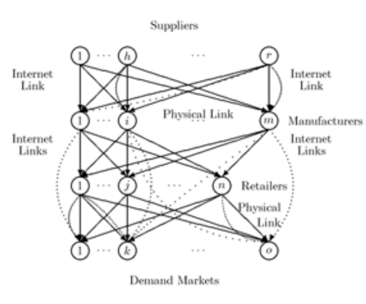
In particular, the supernetwork framework allows one to formalize the alternatives available to decision-makers, to model their individual behavior, typically, characterized by particular criteria which they wish to optimize, and to, ultimately, compute the flows on the supernetwork, which may consist of product shipments, travelers between origins and destinations, financial flows, energy 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.

Supply Chain Networks and Electronic Commerce

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. In today's world, there is growing uncertainty and risk due to various threats and even illnesses such as SARS which have affected dramatically the timely delivery of goods and have impacted transportation of humans as well.

The introduction of electronic commerce has, however, 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. 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.

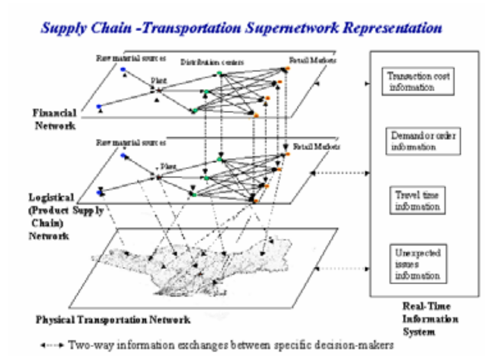
In the next Figure, I depict a four-tiered supply chain network in which the top tier consists of suppliers of inputs into the production processes used by the manufacturing firms (the second tier), who, in turn, transform the inputs into products which are then shipped to the third tier of decision-makers,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

As mentioned earlier, supernetworks may also be multilevel in structure. In particular, Nagurney, Ke, Cruz, Hancock, and Southworth (2002) in *Environment and Planning B* 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.

Below, I recall 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 just depicted, 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 these lines has already yielded promising results (cf. Nagurney, Cruz, Dong, and Zhang (2003) *European Journal of Operational Research*, in press). 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, I 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 as has been demonstrated recently by Nagurney and Fuminori (2003) in

Transportation Research D and is being presently investigated by my group in the context of electric power networks.

Financial Networks and Electronic Transactions

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 supernetworked landscape. Furthermore, the impact of such advances has not been limited to individual nations but, rather, through new linkages, has crossed national boundaries.

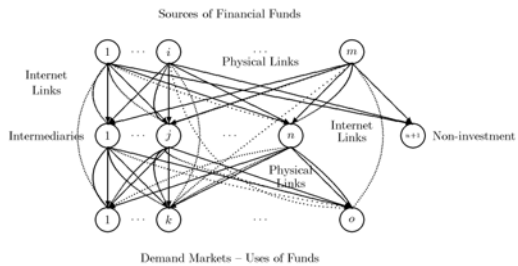
The topic of *electronic* finance has been a growing area of study as described in Nagurney's 2003 edited volume, *Innovations in Financial and Economic Networks,* due to its increasing impact on financial markets and financial intermediation, and the related regulatory issues and governance. Of particular emphasis has been the conceptualization of the major issues involved and the role of networks is the transformations.

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 recently been adressed in unified, quantifiable framework which one can assess the resulting financial flows and prices in a series of papers by Nagurney and Ke and Nagurney and Cruz.

Here, I 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, 2003) in the journal *Quantitative Finance* and Nagurney and Cruz (2003) in *Innovations in Financial and Economic Networks.* 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 the Figure below.



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. We also allow for the option of having the source agents not invest a part (or all) of their financial holdings.

More recently, Nagurney and Cruz in a forthcoming *Computational Management Science* article 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.

In this essay, I have argued for the Supernetwork paradigm as a powerful tool for the study of critical infrastructure networks, emphasizing that it can capture not only the interrelationships among networks but, most importantly, the effects of human decision-making on the induced flows and prices. Through the computation of the flows and prices one can determine the true network designs as well as the associated vulnerabilities. Hence, supernetworks provide not only powerful engineering and operations research /management science tools to bear but also financial and economic ones. Finally, the supernetwork paradigm uniquely captures the human aspects and brings a richness to conceptualization and understanding of the underlying processes.

References are available at http://supernet.som.umass.edu
under "Publications/Downloadable Articles."