NetwORks and Policies: OR to the Rescue

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December 2024; revised April 2025

Journal of the Operational Research Society **77(2)** (2026), pp 656-671

Abstract:

Operational Research (OR), as a discipline, and with its historical foundations grounded in addressing immense challenges associated with WWII, is uniquely positioned to address many of the greatest problems facing the world today from climate change to increasing strife and wars. In this paper, based on my 2024 Blackett Lecture, I overview how our understanding of network systems from congested urban transportation networks to a variety of supply chains, from agri-food ones to blood supply chains, have benefited from OR, and how OR has provided tools for the rigorous construction and evaluation of associated policies for economic and societal benefit. One of the greatest strengths of the OR discipline is the recognition of the importance of a multidisciplinary perspective and the solving of problems through teams. Working together, and engaging in public outreach, we can continue the remarkable, creative legacies of those who have come before us, through mathematical modeling, analysis, algorithm development, the solution of critical network problems, and implementation in practice.

Key words: networks; policies; operational research; supply chains; public outreach

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1. Introduction

I am deeply grateful and very honoured to have presented the 2024 Blackett Lecture on December 5 at The Royal Society and thank the President of The OR Society, Dr. Gilbert Owusu, for the invitation. This paper, based on my lecture, argues for the criticality of Operational Research for the design of policies for network systems that underpin our societies and economies during these challenging times. It is written in the spirit of Lord Patrick Blackett, considered to be the Father of OR, and a Nobel laureate in physics, who, as noted in Kirby and Rosenhead (2011), actively promoted: "the scientist's responsibility to society and the public's need to understand scientific or technical evidence supporting or calling into question public policies." Blackett, furthermore, was an exemplar of "the twentieth century scientist as public citizen" (Nye, 2004, p. 181). Blackett's contributions to the success of the British military in World War II are legendary, with him spearheading operational research groups, early in 1940, which had contributors with expertise in different disciplines, and then becoming Director of Naval Operational Research at the Admiralty (NobelPrize.org, 2024), a position he held until the end of the war.

After receiving two undergraduate degrees from Brown University, I worked in industry for two different firms, over a period of three years, that provided technical services to the Naval Underwater Systems Center in Newport, Rhode Island, while commuting and also pursuing a Master's degree in Applied Mathematics at Brown. The tasks ranged from programming in AN/UYK assembly language routing algorithms for submarines to avoid detection by the enemy to mathematical modeling of data communications networks (cf. Nagurney, 1981). Working in high tech consulting for the naval sector provided an excellent foundation and appreciation for the importance of conducting research relevant to practice. I realized, however, that I did not like having a boss, since I tended to be "too efficient" in terms of project completion, so I headed back to Brown University in pursuit of a PhD in Applied Mathematics, with a concentration in OR (in the US, we refer to OR as "Operations Research"). My PhD supervisor was Stella Dafermos, the second female PhD in OR in the US (see additional background in Nagurney, 1991). Her PhD advisor at Johns Hopkins University was Frederick Tom Sparrow. I was Dafermos's first PhD student. My academic mathematical genealogy through them goes back to Maxwell, Newton, and Galileo (cf. INFORMS, 2024). I always feel that I am "standing on the shoulders of giants" and the framed academic family tree hangs in my office to inspire my students. My love of OR and networks had begun during my undergraduate studies and accelerated during my work in industry and as a graduate student. With multiple offers from both companies and academic institutions, as I was finishing my PhD, I decided to join the faculty of the business school, now the Isenberg School of Management, at the University of Massachusetts Amherst.

My OR journey has been incredibly humbling and rewarding. In this Blackett Lecture paper, I overview some of the background on networks and the research-related themes that I have pursued with many collaborators. In addition, I discuss practical implications and issues. Specifically, this paper is organized as follows. In Section 2, I highlight some of the very early work on networks along with seminal work on congested urban transportation networks, an application that is not only fascinating and, at times, frustrating, but has also stimulated methodological advances and policies such as tolls. Section 3 then revisits the famous Braess paradox (1968), which vividly illustrates the necessity of capturing the behaviour of users of transportation networks (and related network systems) and notes the application of congestion pricing in practice.

Section 4, which consists of several parts, expands on supply chain networks, which may be viewed as critical infrastructure for the production, storage, and transportation of products, both locally and globally. Given the importance of supply chain networks to the functionality of economies and our societies, this section discusses both product perishability in Section 4.1, in the context of supply chains, with applications ranging from healthcare, such as in the case of blood supply chains, to food supply chains. It also notes that, interestingly, certain products obtained via cybercrime may also be viewed as being perishable. In Section 4.2, product quality is discussed in the setting of supply chain networks, since there have been numerous product quality failures, some of which have resulted, tragically, in illnesses and deaths. Emphasizing the importance of interdisciplinary perspectives to the formulation, analysis, and solution of numerous supply chain network problems, here I also highlight how product quality of fresh produce is now being modeled. Minimum quality standards are important policy tools for product quality.

Section 5 further amplifies the research theme of supply chain networks by describing how, in the COVID-19 pandemic, the contributions of essential workers were heroic, and it became apparent that labour needed to be explicitly incorporated into supply chain network models. The urgency to capture many of the intricacies and realities of labour, wages, and the productivity of labour, led to advances in both optimization models and game theory models of supply chain networks, along with suggestions for policies in terms of both immigrant labour as well as greater flexibility of task assignments for labour.

Section 6 then turns to international trade and the many challenges. Here I note such policy instruments as tariffs, of different types, export bans and quotas, and even price supports. This section amplifies the research being conducted with collaborators across the miles on agricultural trade from war-stricken Ukraine, the effects on food insecurity of associated disruptions, and the partnership between universities that is supporting such research. While Sections 2 through 6 overview network-based research themes, Section 7 through 9 focus, respectively, on public outreach, making a positive impact, and a prospectus for the future, accompanied by investments. In Section 7, 8, and 9, I aim to generate additional excitement for influencing policy via OR and our research, and I provide suggestions as to how to proceed. Section 9 also delineates some possibilities for future research.

2. Networks

Networks, from transportation and logistical ones, including supply chains, to telecommunications networks, such as the Internet, along with a variety of economic and financial networks, as well as energy networks, provide the critical infrastructure for the movement of people, the production and distribution of goods and services, and the exchange of information across space and time. Represented by nodes, links/arcs connecting the nodes, plus origin/destination pairs of nodes, along with associated costs, and flows capturing the behavior of "users," network problems have stimulated the advancement of methodologies. As noted in Nagurney (2021a), network theory dates to the 1700s, with the paper by Euler (1736) being the first paper on graph theory, with a graph denoting a mathematical way of abstractly capturing a system in terms of nodes and links. Euler wished to determine whether it was possible to walk around Königsberg (now named Kaliningrad) by crossing the seven bridges over the River Pregel precisely once.

Fascinatingly, one of the first network models was for a financial system proposed by Quesnay (1758) in his Tableau Economique, with the circular flow of financial funds in an economy represented on a network. A few years later, in 1781, as noted in Nagurney (2003), Monge, who had served under Napoleon Bonaparte, published what is considered to be the first paper on the transportation model (see, e.g., Burkard, Klinz, and Rudolf, 1996). Monge was interested in minimizing the cost associated with backfilling n places from m other places with surplus brash with the cost c_{ij} being proportional to the distance between origin i and destination j. Much later, and following the first book on graph theory by König in 1936, the economists Kantorovich (1939), Hitchcock (1941), and Koopmans (1947) considered the network flow problem associated with this classical minimum cost transportation problem, provided insights into the special network structure of such problems, and proposed network-based algorithms. As also described in Nagurney (2003), the formal study of network flows precedes that of optimisation techniques, in general, with seminal work done by Dantzig in 1948 in linear programming with the simplex method and, subsequently, adapted for the classical transportation problem in 1951.

Cournot (1838), in his classical model of a duopoly, which captured competition between firms, considered two spatially separated markets in which the transportation cost was included, and implicitly assumed a network. Pigou (1920), later, investigated a transportation network with two routes and noted that the decision-making behavior of the users leads to different flow patterns. The network consisted of a directed graph, that is, one with the links represented by arrows, plus the resulting flows on the links. Kohl (1841) and, subsequently, Knight (1924) also considered congestion in their transportation network models as had Pigou. Such early contributions anticipated the relevance of economic activity on network infrastructure, along with the users' behaviour. Numerous applications of networks to economics and finance can be found in Nagurney (2021a) and also in Nagurney (1999).

Beckmann, McGuire, and Winsten (1956) in their seminal book, as noted by Boyce, Mahmassani, and Nagurney (2005), formulated and widely analysed a nonlinear optimisation model, whose solution yielded traffic equilibrium flows on a congested network, that corresponded to what is now known as user-optimised flows (see Dafermos and Sparrow, 1969), whereby travellers seek to determine, in a decentralized manner, their optimal routes of travel from origins to destinations. This behavioural concept is in contrast to that of system-optimisation, where the flows between origins and destinations are allocated/routed in a cost-minimizing manner by a central authority. The interest in modeling traffic has fascinated operational researchers as well as those in different disciplines. Even Philip M. Morse, considered one of the Founders of OR in the United States, along with George Dantzig, wrote in his book (cf. Morse, 1977) on page 318: "The delights of research in O/R (he used the slash) are multiple. To me the pleasure coming from understanding how traffic behaves is as great as that coming from understanding how two atoms combine. In addition, the practical applications of O/R theory are often immediate and satisfying." The need to rigorously formulate, analyze, and solve increasingly more general traffic equilibrium patterns on congested urban transportation networks has stimulated methodological advances such as the theory of variational inequalities and its applications, as well as algorithms for the solution of such problems (cf. Dafermos, 1980, Nagurney, 1999).

3. The Braess Paradox and Congestion Pricing

The famous Braess (1968) paradox reveals that, in the case of user-optimising behavior, the addition of a link, which results in a new path, may result in all travellers being "worse off" in terms of increased travel cost/time. Recall that, under user-optimisation, a traffic network equilibrium is achieved if all used paths connecting an origin/destination pair of nodes, that is, those with positive flow, have equal and minimal user path travel costs. The translation of this paper from German to English was done by Braess, Nagurney, and Wakolbinger (2005), with a preface by Nagurney and Boyce (2005) highlighting how Braess discovered the paradox named after him. This paradox has captured the attention of not only operational researchers but also of computer scientists and physicists. It has been identified in the Internet, electric power systems, and even in sports analytics as well as targeted cancer therapy, demonstrating the importance of capturing the behaviour of users of various networks, as well as the underlying network structure (cf. Nagurney and Nagurney, 2021 and the references therein).

In Figure 1, the network topologies are depicted for the Braess networks (the original network and then the one with the addition of the link e). Observe that, in the first network in Figure 1, the origin node 1 is connected to the destination node 4 by two possible paths that travellers can take: path p_1 consisting of links a and c and path p_2 made up of links b and d. In the second network in Figure 1, link e has been added, giving travellers another path option – path p_3 consisting of links a, e, and d. The origin/destination pair of nodes $(1,4)$, denoted by w_1, has a travel demand d_{w_1} of 6 (representing the volume of traffic per unit of time).

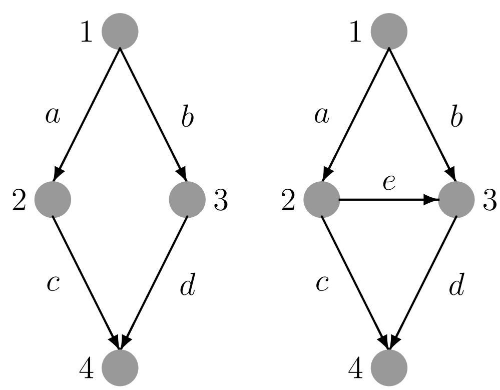

Figure 1: The Braess Paradox Network Topologies

The flows on the links are denoted by: f_a, f_b, and so on, and their respective user link costs by: c_a, c_b, etc. In both these networks the user link cost functions for links a, b, c, and d, are:

$$c_a(f_a) = 10f_a, \quad c_b(f_b) = f_b + 50, \quad c_c(f_c) = f_c + 50, \quad c_d(f_d) = 10f_d.$$

The flows on a path p is denoted by x_p so on the first network in Figure 1 we have x_{p_1} and x_{p_2} as the path flows and, in the second network, also x_{p_3}. As stated in Nagurney and Nagurney (2021), the conservation of flow equations guarantee that the demand for each

O/D pair is satisfied by the flows on paths that connect the O/D pair and that the link flows capture the flows that utilize the particular link. Specifically, the equations state that the sum of flows on paths connecting each O/D pair must be equal to the demand for that O/D pair and that the flow on a link must be equal to the sum of flows on the paths that contain/utilize that link.

Under user-optimising behaviour, the resulting equilibrium path flow for the first network is: $x^*_{p_1} = x^*_{p_2} = 3$, with incurred user path costs of: $C_{p_1} = C_{p_2} = 83$. No traveler has any incentive to switch her path since that would result in a higher cost for her. This result is apparent since the costs on the two paths are: $C_{p_1} = c_a + c_c = 10f_a + f_c + 50$ and $C_{p_2} = c_b + c_d = f_b + 50 + 10f_d$ and, therefore, the travelers at a demand of 6 will equally distribute themselves between the two paths, resulting in the equilibrium path flows: $x^*_{p_1} = 3$ and $x^*_{p_2} = 3$ and the incurred equilibrium link flows: $f^*_a = f^*_b = f^*_c = f^*_d = 3$, with user link costs: $c_a = c_d = 30$ and $c_b = c_c = 53$.

Let the user link cost c_e on link e be

$$c_e(f_e) = f_e + 10.$$

The equilibrium path flow (and corresponding link flow) pattern on the first network will no longer yield an equilibrium for the second network. Indeed, observe that although the costs on paths p_1 and p_2 would be 83, the cost on the new path, C_{p_3}, if it is not used, that is, it has zero flow, would be 70. Some travelers, under user-optimisation, would switch from paths p_1 and p_2 to path p_3 since the cost on path p_3 is less than 83. The switching would continue until the equilibrium pattern: $x^*_{p_1} = x^*_{p_2} = x^*_{p_3} = 2$ is achieved with a corresponding equilibrium link flow pattern: $f^*_a = 4$, $f^*_b = 2$, $f^*_c = 2$, $f^*_d = 4$, and $f^*_e = 2$, with all travelers incurring equilibrium path costs of $C_{p_1} = C_{p_2} = C_{p_3} = 92$. Hence, the addition of the new link/path has resulted in higher travel costs - 92 versus 83 in the original network! This result demonstrates the importance of capturing the behaviour of users of congested networks, and has important policy implications. Indeed, as discussed in Nagurney and Nagurney (2021), removing roads, as has been done in several cities around the globe can actually result in improved travel times. The Braess Paradox does not occur in networks under system-optimising behaviour.

Tolls, also referred to as congestion pricing, are a powerful policy tool that, when calculated correctly, can alter the behaviour of travelers in transportation networks so that they behave individually; that is, selfishly, as in the case of user optimisation, in a way that is also system-optimal. Congestion management is not just an issue in modern times. Even Caesar instituted a time of day policy for chariots to enter Rome, in order to spread out the traffic. Dafermos and Sparrow (1971) and Dafermos (1973) provided explicit formulae for tolls. Tolls have been applied in multiple cities around the globe including London, Singapore, Gothenburg, Stockholm, and Milan (see Mobility, 2022) with congestion pricing in Gothenburg considered to be a big success (see Jaffe, 2015). The imposition of tolls in New York City, previously a topic of avid discussion (see Dolmetsch, 2024), has now become a reality, as of January 2025, at least for now (see Offenhartz, 2025).

4. Supply Chain Networks

Supply chains have become a critical infrastructure for the production, storage, and distribution of an immense range of products ranging from perishable fresh produce and grains essential to food security, clothing, pharmaceuticals, building materials, to computer chips and high tech products, machinery, automobiles, and numerous other consumer items.

The representation of supply chains, which can be local or even global, as networks consisting of decision-makers, stakeholders, as well as associated facilities such as manufacturing sites, distribution centers and warehouses, freight service providers, plus retail outlets, etc., and, in the case of e-commerce, even homes, allows for a rich depiction in terms of the graphical structure (cf. Nagurney, Dong, and Zhang, 2002 and Nagurney, 2006b)). And, when coupled with the underlying behaviour of the decision-makers and stakeholders that includes decision variables, objective functions, and constraints, such supply chain network models can yield important answers in terms of prices, product flows, costs, profits, and, even environmental emissions (see Nagurney and Nagurney, 2010) and waste associated with food (see Yu and Nagurney, 2013)), in such supply chains. Different tiers of suppliers can be incorporated, along with alternative production technologies and storage ones, as well as freight options, represented as links. Decision variables need not be limited to only product flows but can also include quality (see Nagurney and Li, 2016) and even labour availability (Nagurney, 2023).

Having a network representation of a supply chain allows one to identify differences and commonalities associated with different supply chain applications. Furthermore, with rigorous accompanying algorithms for the solution of supply chain network models, one can then perform numerous studies and evaluations of different topologies and investigate questions as to the impacts of addition/deletion of various nodes and links, as well as changes to the objective functions and the constraints (see Nagurney and Qiang, 2009).

For example, Nagurney, Dong, and Zhang (2002), using concepts from game theory, such as the Nash (1950, 1951) Equilibrium, constructed the first supply chain network equilib-

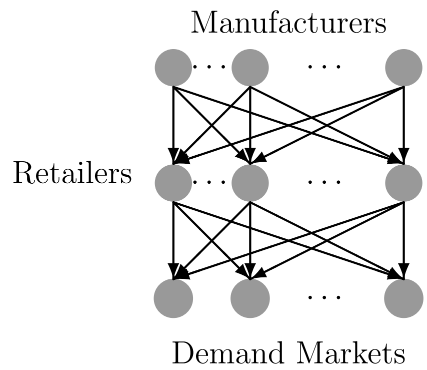

Figure 2: The Multitiered Supply Chain Network Structure

rium model consisting of manufacturers, retailers, and consumers at demand markets. The manufacturers competed across their tier; the same for the retailers, and for the consumers, but for the products to flow between tiers, there was agreement as to the prices (a form of cooperation). For a graphical depiction, see Figure 2. Remarkably, this supply chain network equilibrium model was then shown by Nagurney (2006a) that it could be transformed into a traffic network equilibrium model with elastic demand using the concept of "supernetworks" (see, also, Nagurney and Dong, 2002). Further equivalence between electric power generation and distribution networks, as postulated in Beckmann, McGuire, and Winsten (1956), and traffic network equilibrium problems, as well as that between financial networks and the latter, with resolution of a long-time question by Copeland (1952) as to whether money flows like water or electricity, was established, respectively, by Nagurney et al. (2005) and Liu and Nagurney (2007).

We highlight the work of Li and Nagurney (2017), where a multitiered competitive supply chain network game theory model was constructed, which includes the supplier tier. In the model, the firms are differentiated by brands and can produce their own components, based on their capacities, and/or obtain components from one or more suppliers, also are capacitated. The firms compete in a Cournot-Nash fashion, whereas the suppliers compete a la Bertrand since firms are sensitive to prices. All decision-makers are profit-maximizers with consumers expressing their preferences for the firms' products through the demand price functions associated with the demand markets. Supply chain network performance measures are constructed for the full supply chain as well as for the individual firms. These measures assess the efficiency of the supply chain or firm, respectively, and also allow for the identification and ranking of the importance of suppliers and the components of suppliers with respect to the full supply chain or individual firm. Such tools are very valuable for practitioners since they can further nurture relationships with important suppliers and invest accordingly. Given that the number of disasters is rising, as well as the people affected by them (cf. Nagurney and Qiang, 2009), and even organizations and firms, whose suppliers may be thousands of miles away, being able to rank the importance of suppliers' is highly relevant.

The methodology that has been especially effective in the formulation, analysis, and solution of supply chain network models, both optimization ones and game theoretic ones, has been the theory of variational inequalities, as reviewed in the book by Nagurney (2006b). Therein, a variety of supply chain network equilibrium models are proposed, algorithms outlined, and numerical results for solved examples provided. In addition, the underlying dynamics of the evolution of product flows, product prices, costs of the firms and their profits are also articulated.

4.1 Product Perishability

Perishable products have been the subject of numerous important applications of supply chains and accompanying analyses. Examples of perishable products range from a variety of foods, such as fresh produce, pharmaceuticals and vaccines that require refrigeration, blood products, which must be donated and cannot be manufactured, as well as medical nucleotides, which are subject to radioactive decay, and are used in imaging for cardiac and cancer diagnostics. Even fast fashion can be included under this umbrella with attention also paid to associated waste and environmental costs. The modeling of such supply chain applications requires a multidisciplinary approach, with knowledge of physics, chemistry, and biology. This is in the spirit of Blackett and his teams. For example, red blood cells, used in thousands of transfusions each day for healthcare purposes, have a lifetime of only 42 days, preceded by testing, and accompanied by refrigeration. Fresh produce, even under the best of circumstances, and under proper environmental conditions, once picked, begins to deteriorate in terms of quality.

In Figure 3, several supply chain network topologies are displayed for applications that we have modeled: competitive pharmaceutical firms, a blood service organization, and a medical nuclear supply chain. One can see the various supply chain network economic activities that take place on the links, with associated costs, and the various stakeholders associated with the nodes. The pharmaceutical supply chain network model is an oligopolistic one, governed by a Nash Equilibrium, and the associated game theory problem is formulated and studied as a variational inequality problem. Both the blood service organization and the medical nuclear supply chain network models are optimization models. These, as well as additional applications of perishable product supply chains, can be found in the book by Nagurney et al. (2013).

In our OR work on perishable product supply chains, we make use of generalized networks in order to capture possible commodity losses over space and time. For some background information, see the book by Ahuja, Magnanti, and Orlin (1993) and the papers by Nagurney

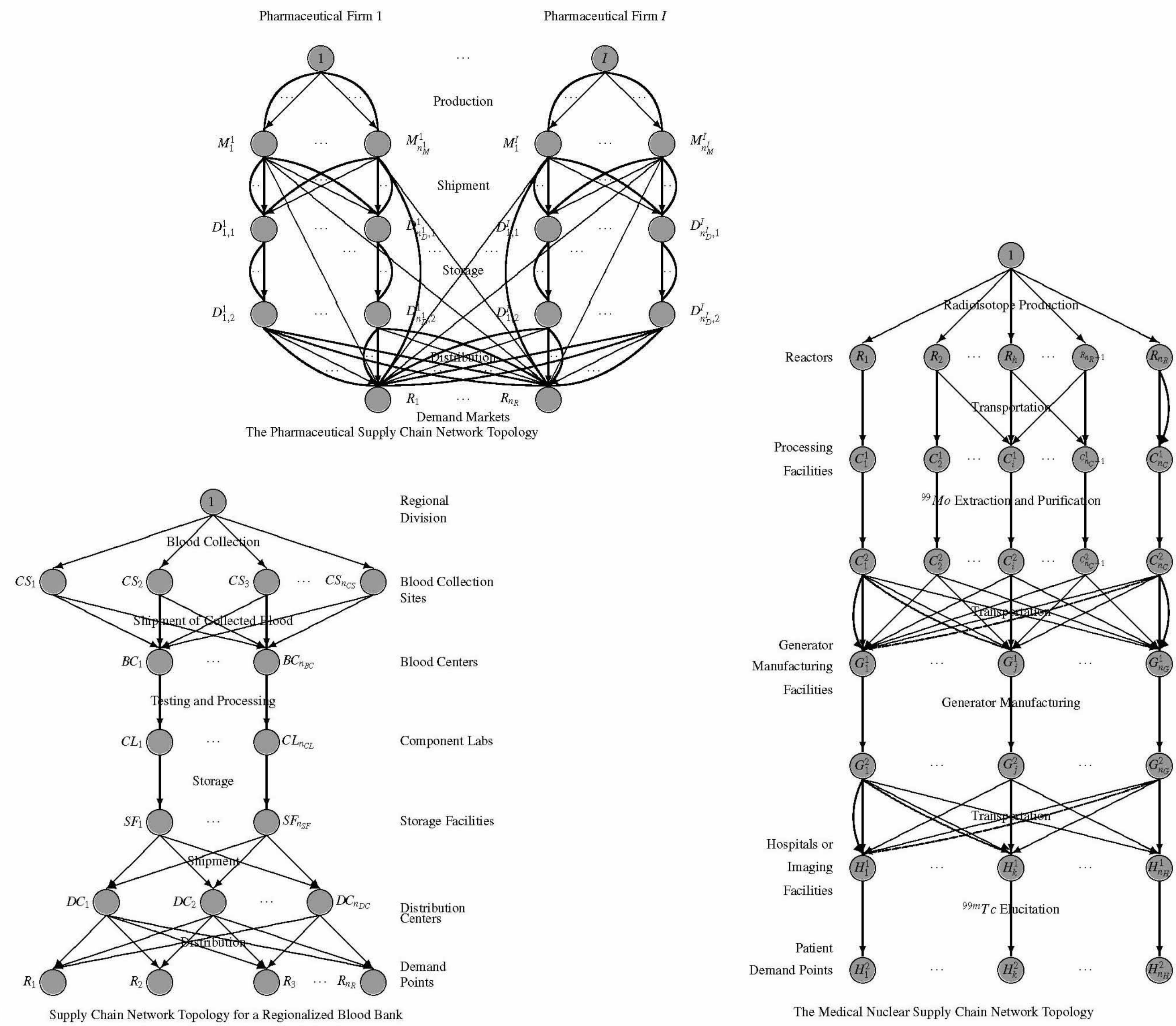

Figure 3: Supply Chain Network Topologies of Several Perishable Products

and Aronson (1989) and Nagurney, Pour, and Samadi (2024), with generalized networks also relevant to finance (cf. Nagurney and Siokos, 1997, and the references therein). In generalized network flow problems, in contrast to pure network flow problems, there are arc multipliers associated with the links and, if their values lie in the range $(0, 1)$ there will be a loss of the flow as it transits on the link; whereas if the arc multiplier on a link is greater than 1, then there will be a gain in the flow as it moves on the link. Clearly, in financial applications, one seeks gains from investments rather than losses. There is no change in the volume of the flow if the arc multiplier is equal to 1. The amount of flow that is "lost" on a link, whether as in the case of fresh produce (see Yu and Nagurney, 2013) or blood (cf. Nagurney, Masoumi, and Yu, 2012), can be considered to be waste, with associated costs of disposal, with special care taken if it is hazardous waste.

Of course, supply chain network models for perishable products for nonprofit organizations, such as blood service organizations, would have objective functions not including profit maximization as in the case of commercial firms. Also, it is important to note that many of the objective functions of organizations involved in perishable products may be multicriteria ones with risk minimization, waste minimization, etc., included and weighted appropriately, in addition to relevant criteria such as cost minimization or profit maximization. And, in the case of disaster management and timely response, additional constraints may be needed (see Nagurney, Masoumi, and Yu, 2015). Uncertainty is also a factor that may need to be captured, whether as in the case of blood collection volumes and/or demand at healthcare facilities and, the case of disaster relief, uncertainty as to the needs of victims at demand points.

Interestingly, in a paper (see Nagurney, 2015), it was demonstrated that hacked credit cards, as targets of cybercrime, are also perishable products, since their value decreases over time. Further, as also proposed therein, through the solution of numerical examples, focusing on financial service organizations, types of interventions are identified, from a policy perspective, that can make it more challenging for cybercriminals to steal sensitive data.

4.2 Product Quality

Quality of products is a very important characteristic and, at times, not sufficiently appreciated until there are major product quality failures. Examples of product quality failures have included: malfunctioning airbags, adulterated pharmaceuticals, bacteria-laden foods, exploding smartphones, and even adulterated infant formula, to name just a few (cf. Nagurney and Li, 2016). Some examples of supply chain network topologies, which correspond to applications in which the quality of products has been investigated, can be found in Figure 4.

In Li and Nagurney (2015), in the context of manufactured products, quality is defined as “the degree to which a specific product conforms to a specification,” which is how well the product is conforming to specifications. When the quality is at a 0% conformance level, it means that the product does not conform to the specification at all, and when it is 100%, the product conforms perfectly. As noted therein, such a conformance-to-specification definition makes quality more straightforward to quantify, which is essential for firms in order to be able to measure quality, manage it, model it, compare it across time, and to also make

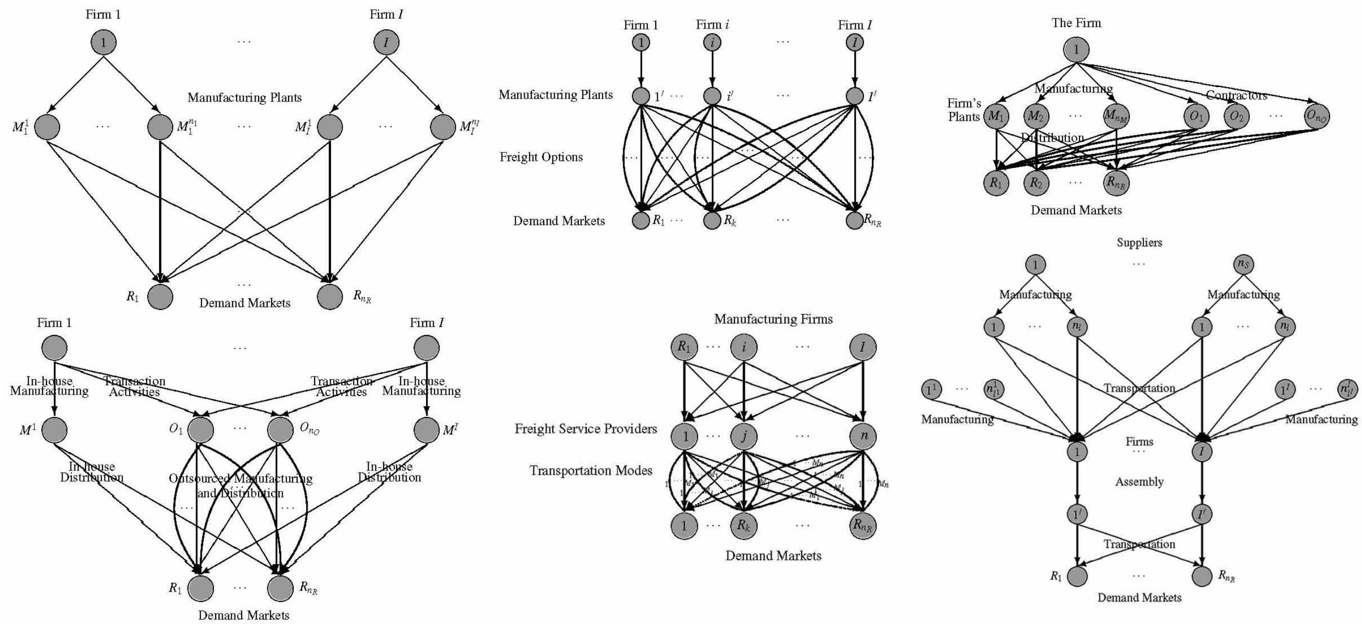

Figure 4: Some Examples of Supply Chain Network Topologies in Which Product Quality Has Been Considered

associated decisions. In the paper, the authors develop a general multitiered supply chain network equilibrium model consisting of competing suppliers and competing firms, who can purchase components for the assembly of their final branded products, and/or, if capacity permits and it enhances profits, manufacture their own components. The decision-makers in each tier of the supply chain network compete, with the suppliers' strategic variables including quality of the components and, in the case of the firms, the quality of the assembly process itself. Minimum quality standards, a powerful policy tool, have been investigated in both oligopolistic supply chain network models and in perfectly competitive spatial price equilibrium models (see Nagurney, Li, and Nagurney, 2014, Nagurney and Li, 2014). For additional background and references, see the book by Nagurney and Li (2016).

Agricultural products, including fresh produce, have been a rich topic of research, in terms of quality, and here, again, interdisciplinarity in the modeling and analysis is crucial. For example, fresh produce, as noted earlier, even under the best conditions, deteriorates after being harvested. In Besik and Nagurney (2017), the authors focused on fresh fruits and vegetables, and, using results from food science for explicit formulae for fresh produce quality deterioration based on chemistry and temperature, constructed quality metrics based on a path-based framework. The model was for farmers' markets and demand depended on both the prices and the quality of the fresh produce. A case study of apples in Massachusetts, under various scenarios, including production disruptions, provided quantitative evidence of the applicability of the competitive fresh produce supply chain network model. In Besik, Nagurney, and Dutta (2023), an integrated multitiered competitive agricultural supply chain network model was proposed in which agricultural firms and processing firms compete to sell their differentiated products. The focus in the paper is on fresh produce and minimally processed such agricultural products, with quality also captured, and with a case study on carrots. Interesting insights are obtained in Besik and Nagurney (2024) for multicommodity fresh produce trade networks with quality deterioration and transportation congestion with applications to the banana trade and routing through the Panama Canal, that has experienced capacity restrictions because of a drought.

5. Labour and Supply Chain Networks

The COVID-19 pandemic dramatically demonstrated the importance of labour, as shortages of labour affected numerous industries from farming and food processing to freight service provision and even healthcare. People were falling ill, millions around the globe sadly succumbed to the coronavirus, and some continue to deal with long-term effects of the disease and the losses. The pandemic, also, revealed the criticality of supply chains and decision-makers took notice. Consumers endured a reduced variety of certain products at supermarkets, and at higher costs, experienced difficulties and long delays in acquiring supplies, such as lumber for construction, and even certain household paper products and cleaning supplies. Hospitals were overwhelmed and healthcare providers, such as nurses, traveled in the US from state to state to provide their much needed services. Certain manufacturers switched from producing products in their portfolios to personal protective equipment (PPEs) and medical equipment, such as ventilators. And, when the vaccine became available, many rushed to sign up. Essential workers from healthcare ones to childcare providers, agricultural and food service sector workers, transportation service workers, and those in critical trades, among others, could not work remotely and their courage, heroism, and service were met with deep appreciation (see ncsl.org, 2021).

Labour, and associated wages, labour productivity, and availability had not been adequately integrated into supply chain network models. Fueled by adrenaline, and the desire to add a deeper level of understanding of the importance of labour to all supply chain network links of production, transportation, and distribution, the first paper that I wrote on the subject developed an optimization supply chain network model for perishable fresh produce. The paper (see Nagurney, 2021c) was published in a Dynamics of Disasters volume (Kotsireas et al., 2021), where other relevant papers on all phases of disaster management can be found. In Figure 5, the supply chain network topology is depicted for the perishable fresh produce model with labour. Note that there are direct links from production sites to consumers since many farmers established outlets in proximity to their farms where consumers could purchase, using online payment systems, what they had harvested.

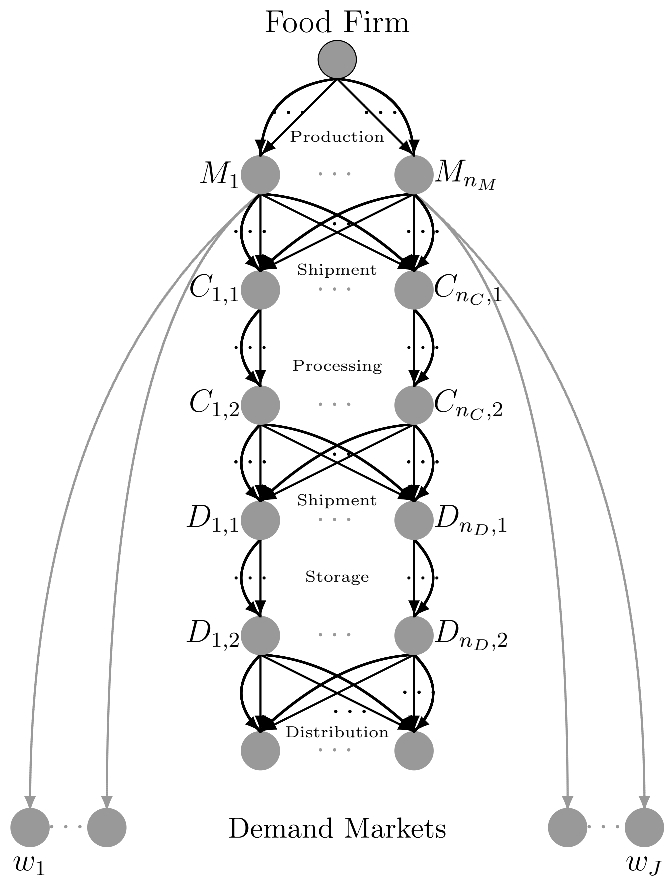

Figure 5: The Perishable Food Supply Chain Network Topology

The COVID-19 pandemic was clearly a disaster and one that was extra challenging, since it was not limited to a location nor to a manageable time period. For the supply chain network model, which was over a generalized network, to capture the perishability of fresh produce, theoretical results were presented plus results from a series of algorithmically solved numerical examples. The results illustrated the negative impacts of a spectrum of pandemic-induced disruptions on the product flows, demands, prices, and the profits of the food firm. Preservation of workers' productivity was important to profitability and including direct demand markets for fresh produce could yield gains for the firm. In Nagurney (2022), an optimization model for a supply chain network with labour was developed in which the firm, subject to a budget, could invest in enhancing labor productivity and wages influenced the availability of labor.

In Nagurney (2021d), several game theory supply chain network models were proposed under distinct sets of constraints on labour with bounds on labor availability on each link investigated first and then bounds across a tier of links such as manufacturing, transportation, storage, etc., and, finally, a single bound on labor availability with workers, assuming appropriate skillsets, reallocating across firms and supply chain network activities. The latter two models were no longer governed by the classical Nash Equilibrium but, rather, by a Generalized Nash Equilibrium since the firms' constraints were no longer independent of one another's. The methodological tool for the formulation, analysis, and solution of the models was that of variational inequalities. Having the flexibility of workers moving across different activities yielded gains and this was also found to be beneficial in practice (see Nagurney, 2021d). For some insights on the efficiency and resiliency of supply chain networks to labour disruptions, see Nagurney and Ermagun (2022). The book Labor and Supply Chain Networks (Nagurney, 2023) contains numerous supply chain network models with labour and various policies. There are models included not only for commercial firms but also for nonprofits, such as blood collection organizations and disaster relief agencies. The impacts of migrant workers and the payment of fair wages in supply chain networks are also investigated therein. Human migration, over the past several years, has also been investigated from a policy perspective. For example, Nagurney, Daniele, and Cappello (2021) demonstrated that, through policy interventions, in the form of subsidies, a system-optimum for a multiclass human migration network could be achieved, despite the migrants, which could be refugees, behaving in a user-optimised manner. The work was influenced by tolls for altering the behaviour of travellers, but applied to a different time scale (see, also, Nagurney and Daniele, 2021).

6. International Trade and Challenges

In the COVID-19 pandemic, many governments in countries around the world instituted various trade policy measures, with the aim of protecting their citizens, specifically, from various product shortages, and with the hope of increasing domestic supplies (see, e.g., Evenett et al., 2022). These trade policies included export and import controls. And, these days, trade policies such as tariffs are, again, major news, along with trade wars (see Lipsky, 2024, Bednar, 2025, Boak, Wiseman, and Gillies, 2025, and Lu, 2025). OR has been instrumental in the rigorous modeling of various trade policies, usually in the framework of fundamental equilibrium models. For example, Nagurney, Besik, and Dong (2019), using variational inequality theory, developed a unified framework for tariffs and quotas, including tariff rate quotas (TRQs), which are two-tiered tariffs, and applied the results to dairy trade. As noted therein, the Uruguay Round in 1996 induced the creation of more than 1,300 new TRQs, including on commodities of various food staples such as wheat and corn, essential for food security. The model was a spatial price equilibrium (SPE) model, significantly extended the classical SPE models models of Samuelson (1952) and Takayama and Judge (1971), with the first variational inequality formulation of the SPE conditions done by Florian and Los (1982) and sensitivity analysis results obtained by Dafermos and Nagurney (1984). See also the earlier work of Nagurney, Nicholson, and Bishop (1996).

Nagurney, Salarpour, and Dong (2022), in their multicountry, multicommodity SPE model with trade policies, including price floors and ceilings, focused on essential products in high demand in the pandemic, including medical supplies. As noted therein, when the COVID-19 pandemic pummeled one country after another, some countries, which were among the few exporters of PPEs, faced a very high demand within their own national boundaries. They, hence, prioritized meeting their citizens' needs first and banned medical product exports. Nagurney, Salarpour, and Dong (2022), also reported that, following the Global Trade Alert (GTA), as of 25 April 2020, 122 new export bans in more than 75 countries including the US, China, and the European Union (EU) were issued on medical supplies such as antibiotics, face masks, and ventilators. Also, many countries, including China, reduced tariffs on essential products to speed up their import.

The above highlighted models with trade policies have been perfectly competitive ones. There is also research on trade policies, such as tariffs and quotas, in the context of supply chain network equilibrium problems. An example is the model of Nagurney, Besik, and Li (2009), which is an oligopoly model (and, therefore, assumes imperfect competition) in which firms compete on both quantity and quality until a Nash Equilibrium is achieved. In the paper, it is shown that quotas can be constructed in a way that yields the same equilibrium solutions as that of tariffs, providing decision-makers with flexibility.

The 21st century has clearly brought many challenges, from the COVID-19 pandemic, to climate change, and heightened geopolitical risks, including wars. On February 24, 2022, Russia launched a full-scale invasion of Ukraine, and the war on this European country is continuing, now for almost 3 years. Ukraine, considered to be the breadbasket of Europe, if not the world, because of its rich black soil, known as chernozem, has been a major exporter of wheat, corn, and sunflower oil. The destruction of agricultural lands in Ukraine, the mining of them and parts of the Black Sea, along with the killing of farmers and other civilians, and rising costs associated with farming as well as labor shortfalls because of the war have added to rising global food insecurity especially in Middle Eastern and Northern African (MENA) countries, in terms of both increasing prices of staple commodities and reduced trade volumes.

In March 2022, the University of Massachusetts Amherst (UMass Amherst) and the Kyiv School of Economics (KSE) established a partnership (cf. University of Massachusetts Amherst, 2022), which, to-date, has supported two sets of cohorts of Virtual Scholars in Ukraine, who are partnered with faculty at the University of Massachusetts on research projects. It has also supported two sets of exchange students from KSE, last year and this academic year. Working with colleagues at KSE and a doctoral student at the Isenberg School of Management, Dana Hassani, we have written a series of papers on the impacts of the war on agricultural trade with a focus on exports from Ukraine (see Nagurney et al., 2023, 2024a,b and Hassani et al., 2025). The paper of Nagurney et al. 2024a tracks exchange rates over routes that the agricultural commodities take, which can involve transit via distinct modes (rail, barge, ship, etc.) from points of origin to destinations. The variational inequality model also includes tariffs, quotas, and subsidies for farmers and computed solutions to numerical examples demonstrate the benefits in terms of consumer prices and volumes of commodity shipments, under subsidization. In Nagurney et al. (2024b), a multicommodity international trade network equilibrium model is constructed under capacities on production and transportation, as is happening in wartime in Ukraine, with farmers having to choose which agricultural commodities to produce and how to transport them. The model is also relevant to different existing scenarios that the world is facing with climate change reducing the amount of land for planting and even the Panama Canal Authority, because of a drought, having to reduce the number of ships transiting through the canal (see Associated Press, 2024). The above-noted studies also investigate the effects of the Black Sea Grain Initiative brokered by the United Nations and Turkey and its cessation by Russia. A multiperiod, multicommodity trade network equilibrium model proposed by Hassani et al. (2025), in turn, includes capacities on storage of agricultural commodities, since grain silos in Ukraine have also been destroyed by Russia. A network representation of the multiperiod structure of the model is given in Figure 6. The horizontal links correspond to storage over time.

Given that both sudden-onset and slow-onset disasters are disrupting global trade, and impacting both the availability and affordability of commodities such as agricultural ones and even minerals, modeling various scenarios under uncertainty is an important endeavor. In Nagurney et al. (2024b), a multicommodity international trade network equilibrium model was constructed under disaster scenarios. The scenarios were associated with distinct probabilities of occurrence and different impacts on the capacities on production, transportation, and consumption at the demand markets, as well as on the exchange rates. For each disaster scenario, an international trade network performance measure was identified. A unified performance measure that includes all the disasters and their probabilities was then constructed, with robustness also quantified. An international trade network component performance in-

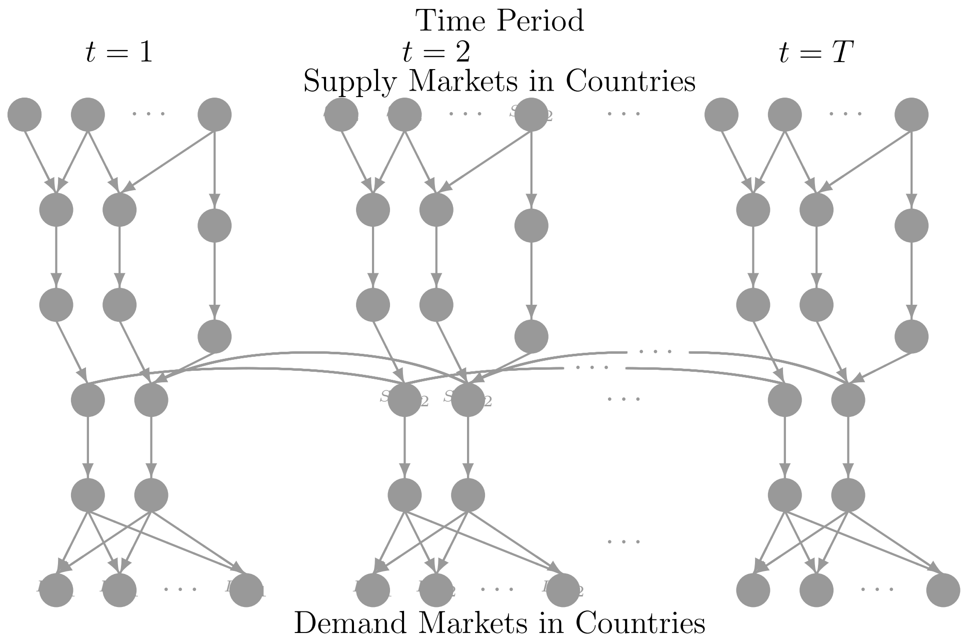

Figure 6: A Multiperiod International Agricultural Trade Network Topology

dicator was also introduced to measure the impacts of the complete removal/destruction of supply markets, demand markets, and/or transportation routes, thereby, allowing for their ranking in terms of importance. The relevance of the modeling framework was then shown, via a series of numerical examples, drawn from Russia's war on Ukraine. The model can be adapted, with appropriately parameterized data for the underlying functions, to investigate a multiplicity of ongoing international trade challenges, due to disruptions, including the impacts of the Houthi attacks on the Red Sea. Many ships are now rerouting with their cargo around the southern tip of Africa, the Cape of Good Hope, because of the perils of the area, including the Suez Canal (cf. Power, 2024).

7. Public Outreach

As important as research is in our profession, and for those of us who are academics, publishing as well, in order to make positive change, public outreach serves as an important avenue in which to reach a variety of stakeholders, constituents, and decision-makers and policy-makers. Reaching out to the public can be achieved in many forms by writing, for example, Letters to the Editor to your local newspapers or national and international ones, as well as magazines. It can take the form of writing OpEds on various platforms and further promoting and publicizing relevant results and studies via social media. For example, once I have several publications on a topic that I think is particularly timely, I will write an article for The Conversation, which, according to its website (see The Conversation, 2024): "is a nonprofit, independent news organization dedicated to unlocking the knowledge of experts for the public good." There are editions in the US, the United Kingdom, Canada, and Australia as well as other countries. Articles published therein are distributed to other news platforms across the geographic spectrum. My article on the global shortage of shipping containers at the height of the COVID-19 pandemic (cf. Nagurney, 2021b) has amassed over 350,000 reads and has even been assigned reading material in various university classes. Given my research on game theory and disaster management, and my concern over shortages of various medical supplies, including PPEs, in the pandemic, I published an article in The Conversation (see Nagurney, 2020a) on how game theory can help us to make sense of the fierce competition for such supplies. Because of concern as to whether the ultra cold chain infrastructure was in place to keep the vaccines safe, and even before the vaccines were available, I wrote an article in The Conversation on the importance of storing the coronavirus vaccine at below zero degree temperatures (see Nagurney, 2020b). And, more recently, using a combination of my expertise in labor and supply chain networks, as well as perishable products, including fresh produce, I wrote an article highlighting the potential ramifications of the dockworkers strike on the East Coast of the US (see Nagurney, 2024a), which, luckily, and, perhaps through all the writing and publicity, got paused, only several days afterwards (Nagurney, 2024b).

Publications such as OpEds, and even Letters to the Editor, can generate invitations to speak to the media, on radio and television, as well as on podcasts, and also can result in interviews for newspapers, magazines, etc. The requests usually require a timely response, since news these days happens at such a lightning pace and experts are in high demand. I have enjoyed being interviewed by journalists from The New York Times, The Washington Post, The Wall Street Journal, the Associated Press, CNN, Reuters, and the BBC, among others, and have appeared on news programs, both nationally and internationally. I must add that not every interview may result in your quotes appearing. I have had cases where I have spent about an hour informing a journalist on a topic and nothing came of it except that my role as an educator was expanded. Other journalists have asked such intriguing questions, that new research directions for me have come about. I appreciate the challenge of speaking with the media and also the professional growth. Doing so is a valuable type of public outreach and can be very rewarding. It also enhances the visibility of the OR discipline. I do have my limits, however, and will not be interviewed for live shows after 10:30 PM.

8. Making a Positive Impact

Of course, whether as academics or practitioners, we would all like to make a positive impact and, through our employment, we do so for our organizations (and our clients). Here, however, I am interested in how to have a broader impact as in helping society through OR, that may be an outgrowth of one's expertise and research. Many in our great profession did our best to inform the public and even legislators and government officials during the pandemic, since knowledge on supply chains, healthcare, and even education was badly needed, was evolving, and it was imperative that it be shared. I think that, many of us, because of our global connections and community, were well aware that there was a healthcare crisis happening, even before the World Health Organization (WHO) declared the COVID-19 pandemic on March 11, 2020 (see Cucinotta and Vinella, 2020). I noted, for example, that there were blood shortages in various countries and, the day after the pandemic was declared, my article, "How Coronavirus is Upsetting the Blood Supply Chain," was published in The Conversation (cf. Nagurney, 2020c). INFORMS then invited me to publish an updated article on the topic, which appeared in its Analytics magazine on March 24 (see Nagurney, 2020d).

Journal articles may take a long time from submission to publication; the same for them making an impact. My Conversation blood supply chain article, on the other hand, was impactful quickly. On April 22, 2020, Xavier Becerra, at that time the Attorney General for California, sent, via electronic mail, a letter to then The Honorable Admiral Brett Giroir, MD, Assistant Secretary for Health U.S. Department of Health & Human Services, which was signed by 21 other Attorneys General, including Maura Healey of Massachusetts (see oag.ca.gov, 2022). The letter proposed revised "guidance as an important first step for protecting the nation's blood supply, especially during these unprecedented times." My Conversation article was cited in a footnote on the first page. Becerra became the US Secretary of Health and Human Services in President Biden's administration and Healey is now the Massachusetts Governor. The letter influenced national policy on blood donations.

During the pandemic I was also called to serve on a Task Force in the state of Massachusetts to advise on improving distribution of the COVID vaccines. Furthermore, in 2024, I was appointed to serve a five-year term as a Supply Chain Expert in the Science Advice and Guidance for Emergencies (SAGE) program. This program is "an Office of Enterprise Services, Administration and Support Division program with a direct link to the Chief Scientist Office in the Department of Homeland Security (DHS)" (University of Massachusetts Amherst, 2024).

9. Prospectus for the Future and Investments

The discipline of OR is in excellent shape with the research and scholarship contributing to decision-making and innovations in numerous sectors such as agriculture, manufacturing, transportation, defense, healthcare, energy, and education, to highlight just a few. Students are clamoring for courses in OR-related subjects, with analytics classes as well as AI ones in high demand. And, as during the founding period of OR, our expertise is increasingly sought by governments and various organizations, including nonprofits, from those at local and regional levels, to national and international ones. Graduates of our programs are in demand by tech companies, government institutions, healthcare organizations, consultancies, financial service firms, logistics / supply chain firms, retailers, among others. Professional societies such as The OR Society, the Institute for Operations Research and the Management Science (INFORMS), and the International Federation of Operational Research Societies (IFORS) are contributing to knowledge discovery and professional support and advancement through journals and other publications, conferences, and various networking and educational events and even certifications. They are also assisting in bringing findings of operational researchers to broader audiences.

It is important that OR continue to be recognized and valued and that the community is enriched with all voices. The challenges facing our beautiful planet are immense, as highlighted in this paper, from climate change to heightened geopolitical risk, violence, and strife, and growing food insecurity. Writing and speaking out will be critical. I am grateful to the Editors of the Journal of the Operational Research Society for the publication of its discussion paper by Carroll and Amideo (2024) on gender equality and the challenges and opportunities for the OR community, followed by the commentary on the paper by Albert et al. (2024). Addressing many of the problems will require the best minds, rigorous tools, creative perspectives, and practitioners and academics collaborating, and communicating and sharing their results with decision-makers, including governmental officials and legislators. By working together, as the teams of Blackett did in WWII, we can harness our energy and skills for the betterment of our planet and mankind. Present and future OR research needs mandate that we tackle climate change, impacts of war on people and the environment, increasing poverty and disasters of many forms, global polarization, disruptions to global supply chains, the spread of diseases, disaster management and response, inequities, including healthcare and education inequities, migration, challenges in agriculture and escalating insecurity, including that in the cyber space. OR, I am certain, will lead in the advancement of AI/OR integration, the design of effective, rigorous policies for a plethora of network systems, the innovations needed in terms of methodologies for prescriptive analytics, and the harnessing of technologies coupled with optimization, simulation, and game theory.

But investments will be needed. Documentation of OR success stories, and the individuals that contributed to them, can help in dissemination and in inspiring others. An example is that of the website INFORMS Biographies: `https://www.informs.org/Explore/History-of-O.R.-Excellence/Biographical-Profiles`. Attracting additional students to OR and showing the possibilities, can be attained through books, articles, as well as videos, such as the remarkable constellation of the latter, done through the herculean efforts of Anand Subramanian, with over 100 conducted interviews now posted on youtube (see Subramanian, 2024). Broadening the recognition of OR and its great applications is being initiated by groups even in secondary schools (see Colajanni et al., 2024). Learning from expert female researchers in a comfortable setting, is the subject of a journal article by Amorosi et al. (2021). Another outstanding publication, focused on inspiring interest in STEM fields in girls, is the book by Stephanie Espy (2016), STEM Gems: How 44 Women Shine in Science. I was honoured to be featured in this book because of my contributions to the study of network systems. Operational researchers, with their expertise, experiences, knowledge, and creativity as well as networks will continue their impactful scientific contributions, now needed, more than ever.

Acknowledgments

I am grateful to the Editor-in-Chief of the Journal of the Operational Research Society for the invitation to write up my Blackett Lecture and also thank the anonymous reviewers and the Associate Editor for constructive comments and suggestions on an earlier version of this paper. I acknowledge all who have contributed to the OR discipline and who have helped to build a truly remarkable scientific community. I thank my teachers, collaborators, and students for enriching my OR journey as well as family members for their support.

Disclosure statemet

No potential conflict of interest was reported by the author.

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