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Article

Challenges in Digitalization for a Holistic and Transparent Pandemic Supply Chain

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Abstract

Covid-19 supply chain disruptions clearly illustrated deficiencies in central coordination. Meaningful improvement in central coordination of supply chains will require transparency into resource stocks and flows. Latest technology, like 5G, blockchain and IoT, are primed to provide this transparency for collaboration during pandemics. This will improve agility and service, reduce inventory and enable reverse logistics benefits. Furthermore, transparent global networks can allow more inclusive and equitable distribution of critical supply, yielding quicker resolution to pandemics. However, many challenges exist that portend to delay the adoption of a holistic and transparent digitalized supply chain. This paper explores the most recent pandemic with attention to the limiting factors at all levels of emergent global crisis response.

Keywords: operations management; digitalization; 5G; blockchain; IoT; supply chain management; supply chain transparency; visibility; central coordination; crises; COVID-19 pandemic; risk mitigation

1. Introduction

Operations management utilizes strong central coordination to directly and indirectly execute necessary processes to accomplish organizational objectives. This central coordination relies on timely data access across organizational supply chains. These are irrefutable principles in modern organizations, proven in operations research and practiced in operations management. Organizations extend their data visibility up and down supply chains, benefiting various stakeholders. What supply chain disruptions during the Covid-19 pandemic illustrated, is that data visibility between various supply chains remains extremely limited. This lack of transparency continues to constrain timely, efficient central coordination in a crisis.

As relevant central coordinators lack real-time visibility into global supply chains, they are unable to tap available resources quickly. Existing stockpiles and production capacity are at risk of languishing, while various stakeholders compete for any known supply. The sub-optimized nature of organizational supply chains is to the detriment of the public. If the total available supply of raw materials and inventories, combined with total production and distribution capacities, were mapped in real-time, central coordinators with stakeholder agreed permission could rapidly commit, deploy, allocate, and re-deploy during crises. Instead, central coordinators are left with opaque visibility and lags in response, due to the de-coupled nature of each organization's supply chain data.

The step-change the authors call for in this paper, is the seamless, automated, and secure integration of various supply chains, to finally allow inter-organizational visibility to existing global supply, capacity, and capability. Latest technologies are sufficiently proven, mature, and robust, to allow confidence in their application. Relevant examples include 5G cellular, blockchain, IoT devices, RFID, and various secure encryption schemes. These system investments can be further leveraged through application of AI, big data analytics, and machine learning, for modeling, optimizing, and stress testing global supply chains. Current technology implementations remain at the organizational

level, at best with upstream and downstream data links. The authors call for an open standard system architecture to allow various stakeholders to engage real-time, inter-organizational supply chain data on rules-based consensus.

2. Literature Review

In spite of academic and practical relevance, the authors' literature review suggests this proposed step-change in interorganizational supply chains offers a novel innovation to a topic of contemporary concern. While the authors' work links explicitly to the actual, relevant, managerial challenges of operations during this pandemic, the integration of data-secured supply chain transparency also improves upon the practice of operations management in general. The following literature review synthesizes the ongoing technology adoption and evidence-based operational adaptation, inherent in real-time Covid-19 pandemic response, with foundational scholarly literature appropriately grounded in theory. The authors advance the ongoing conversation and offer novel and interesting insights which are likely to motivate future research that will substantially change operations management theory and practice.

The authors surveyed current literature in relevant areas, such as humanitarian supply chains, disaster-relief supply-chain management, and logistics operations for epidemic control, to identify gaps in current practices and academic literature and to suggest opportunities for future research and innovation. Specifically, the authors were interested in new paths of business transformation enabled through adoption of digital technologies, big-data analytics, and innovations in the design of supply chain networks and governance mechanisms. There are key lessons to be learned from any large-scale disruption in supply chains, including optimal terms for selecting and managing supplier and customer relationships, designing global supply networks, and adopting latest innovative digital technologies and big-data analytics. This paper draws from contemporary literature to contribute managerial insights and guidelines for practitioners to improve responsiveness, resilience, and restoration of supply chains.

Vulnerabilities to foreign interests revealed by Covid-19 are of particular concern for supply chain and operations managers. Before this pandemic, China produced approximately half the world's face masks. As the infection migrated from Wuhan throughout Hubei Province, and then on to other countries, Chinese government and its dependent firms acted in their own interest by seizing inventories of goods and manufacturing capacity for N95 masks and other critical items (Ranney et al., 2020). Chinese exports for personal protective equipment (PPE) came to a halt; as a result, US businesses, along with global captive markets could not supply their customers, including government and healthcare sectors. These disruptions included both outsourced production and US companies with manufacturing facilities in China. While China avoided trade restrictions on PPE, the priority was domestic production for the home market. Products set-aside for global export were subject to traditional brokers and agents with entrenched trade relationships based in guanxi, limiting open-market competition and reducing the available stock for all other trade partners. To satisfy the lack of global demand, unregulated producers supplied sub-standard and spuriously labeled products, taking advantage of the captive market; yet Chinese production could still not achieve the necessary volume of PPE production while adhering to the quality standards required. The delay and outright opportunism created by desperation for epidemic prevention necessitated the pursuit of many local or domestic solutions, including the providence of masks and PPE by virtue of the Defense Production Act (DPA) in the United States, as well as instances of near shoring and adaptive industry where companies realigned their operations to make necessary products at the cost of other manufactured goods; as in the case of automakers and fashion brands converting production to masks and ventilators.

The cascading effect of those immediate market constraints in China then created a ripple effect of similar actions by nations concerned at an outflow of their own critical PPE and medical supplies. According to a report from Financial Times (2020), the reshoring argument was given impetus by the big shortage in the first few months of the pandemic in medical equipment and particularly PPE.

Countries with manufacturers slammed on export controls to ensure their products were kept at home. “There was not even solidarity within the EU, supposedly a seamless single market and trading bloc. Germany put export bans on face masks to Covid-hit Italy, and member states such as France even tried to snaffle kits that happened to be passing through the country.” (Financial Times, May 27, 2020)

Firms naturally seek to manage risk, especially following idiosyncratic shocks like Covid-19. Companies will re-assess their global exposure to offshore production, their decreased control from outsourcing, and will explore new opportunities in the medical industrial complex. As the adage goes: ‘companies do not compete, their supply chains do.’ But in an effort to mitigate the prevailing risks of this most recent pandemic, technology solutions provide the expedient controls necessary to reduce the impact of the spreading infection on industry and economy, mediating the lack of transparency in existing supply chains. Big data, residing on cloud platforms, captured via IoT, and securely communicated via blockchain, can all be brought together for real-time visualization of firms’ global supply chains.

The authors find indications that companies that have higher levels of adoption of digital technologies are better positioned to respond to supply chain uncertainty and are more resilient to supply-chain disruptions. When armed with appropriate digital technologies, 3-to-5PL’s have adapted to new digital demands (Zhuckovskaya et al., 2020) and open-source communities have overcome adverse conditions to provide essential supplies for healthcare workers (Pearce, 2020). Other supply chains used IoT and digitalization to recover consumer food stocks (Yadav et al., 2020). A comprehensive literature review by (Golpîra et al., 2021) of IoT trends in research suggests primarily qualitative analysis over the past 12 years, with quantitative analysis become more prevalent in recent years. Some companies have successfully exploited existing industrial internet platforms to procure medical supplies from global sources to meet demand. There is also evidence of growing collaboration between government, non-profit, and for-profit organizations to expedite critical medical supplies, such as PPE.

Between 2008 and 2018, global trade in PPE and medical devices has more than doubled in value (Bamber et al., 2020). The driver was a large increase in demand, resulting from a rapidly aging population in both rich and middle-income countries, increased expenditure on healthcare in the developing world, and low tariffs that resulted in a plentiful supply of low-priced and high-quality goods. According to data from the US Department of Health and Human Services, 95% of surgical masks and 70% of respirators are produced overseas (Urgent Care Association, 2020). While the market share for PPE is globally distributed (North America 33%, Asia and the Pacific 28%, Europe 22%, Latin America 11%, Middle East and Africa 6%), the production heavily concentrates in Asian countries with masks largely in China, gloves largely in Indonesia, Malaysia, and Thailand (Asian Development Bank, 2020).

It is clear that we need international-level transparency to facilitate response to a global health crisis such as Covid-19. Central coordination of supply requires transparency of materials stocks and flows including locations, volumes of standardized varieties and compatible alternatives. Basic PPE supply chain data, such as the production quantity in each facility, is treated as confidential and typically not disclosed to government agencies, the public, or company shareholders. A recent study, examining the past five years of financial disclosures for three major PPE manufacturers and conducting an exhaustive search of more than 1,700 media reports about the PPE supply chain published between January 14 and April 26, 2020, found no basic supply chain data, including, for example, the exact domestic vs. foreign capacity of N95 masks (Dai et al., 2020). Van der Laan, et al. (2020) offer that, “considerable bias appears to exist towards over-forecasting of consumption” continuing that “bullwhip-like effects may occur, resulting in unnecessarily high stock levels that are prone to obsolescence.” Particularly relevant to pandemic PPE they state that, “The medical team has an incentive to overestimate demand, in particular for slow moving, intermittent demand items, to ensure that they have inventory at hand in the case of an emergency.” Very early in this pandemic, unapproved products had already supplemented approved products in critical care environments,

both as handmade, reusable masks and as disposable masks packaged for limited or single use, that are being treated with hydrogen peroxide vapor to extend useful life between 30 and 50 uses (Maia Chagas et al., 2020; Schwartz et al., 2020). The actual practice of decontamination is considered a last resort in lieu of supply chain failure. The prevailing response to lack of supply chain capability and capacity, at least in the United States, was to access any available alternatives for re-purposing and innovating substitute products of satisficing quality but immediate availability. While this trend is a notable testament to the resourcefulness inherent in times of crisis, long-term commercial supply chains failed to achieve their intended purpose, undermining public trust in both quality and availability assurance.

The responsiveness of open-source and distributed sharing to provide for the lack of supply chain effectiveness may be one of the most notable successes of the Information Age. Designs to make shields and accessory items like mask buckles can be found in wide variety online and require only desktop 3D printers (Rindfleisch, 2020); yet, there often exists no formally regulated pathway for locally manufactured PPE to enter the clinical or hospital setting, as evidenced by the introduction of 3D printed face shields into a hospital (Mostaghimi et al., 2020) as a solution of last resort. The US American National Standards Institute (ANSI)/International Safety Equipment Association (ISEA) Z.87.1-2015 standard specifies nearly twenty required physical features of a face shield, as well as testing requirements for visual resolving power, resistance to high-velocity impacts, and protection from droplets and splashes. Facemasks are classified by the FDA as low-risk (Level I) Medical supplies, and therefore may benefit from expedited approval for use, if such a process did exist for flexible manufacturing of locally distributed medical goods.

Research on the prevention effectiveness of masks versus respirators predates the current pandemic, principally on Tuberculosis and Influenza. However, recent evidence suggests the benefit of superior prevention effectiveness by continuous N95 uses compared to medical mask use was questionable (Mukerji et al., 2015). Even as recent as March 2020, the National Institutes of Health published evidence evaluating the cost-and-clinical effectiveness of masks for unvaccinated healthcare workers in acute or long-term settings to treat influenza (Marchand, 2020), determining no cost effectiveness and unclear clinical effectiveness with no evidence-based guideline regarding the use of masks to prevent influenza. More studies show that surgical masks or N95 respirators were the most consistent and comprehensive supportive measures, while N95 respirators were non-inferior to simple surgical masks but more expensive, uncomfortable and irritating to skin (Jefferson, 2011). These findings are supported by the study showing that the incremental cost to prevent a clinical respiratory illness was US \$490-\$1230 more with an N95 Respirator strategy versus a medical mask strategy, at the same time suggesting that use of N95 respirators would still be a cost-effective intervention during a pandemic (Mukerji et al., 2015). Studies reported that within 1 month, 116 P100 respirator and cartridges replaced 2,088 N95 Respirators per day, reducing the usage of disposable masks by 75% compared to a reuse and sterilization program (Chalikonda et al., 2020).

As early as March 28, Provenzano et al. (2020) supplied evidence to the effectiveness of rapid prototyping of a reusable N95-equivalent respirator at George Washington University, made utilizing 3D-printing technology and a cost per filter of \$.10 and a cost of about \$3.00, competitive with the cost of one disposable medical mask and a potential on-site delivery capacity of 70-100 masks in a 24 hours period. The sustainability of a multi-use, cost-efficient product such as this, made from a renewable source such as plastics can maximally reduce the environmental impact of disposable alternatives, as 1,000+ filter cartridges can be produced from a single MERV 16 air filter.

However, the US Department of Defense (DOD), has consistently relied on large contractors to supply the majority of PPE in response to COVID-19. In much the same response as the lesser Ebola outbreak in 2013-2014, the DOD has relied on a handful of very large contractors to supply the majority of PPE, with the top 10 contractors contributing nearly 90% of all contract value, 5 entities controlling 80% of contract spend between 2013-2019, and nearly half of all 2015 dollars going to a single contractor. The surge of PPE costs in that time frame by the DOD to \$40 million pales in comparison to the \$634 million currently being spent on masks and N95 respirators alone (DOD,

2020). The US government has not been idle in explaining the inadequate management of critical PPE. The Office of the Inspector General in 2014 issued a clear report stating the Department of Homeland Security had failed to perform a needs assessment prior to the purchase of its stockpile, of which most PPE is nearing expiration or is already expired. 84% of stored hand sanitizers were expired and 200,000 respirators were past their five-year guaranteed manufacturer's use date (DHS, 2014). Similar incidents of excess expired equipment were also noted in Canada and Australia during audits that date prior to the Covid-19 Crisis (Laing et al., 2020). Of \$750 million spent by Australia over 10 years, \$250 million in stockpile goods were expired, requiring another \$75 million to dispose (Australian National Audit Office, 2014). The Centers for Disease Control and Department of Health and Human Services estimate that a severe pandemic like the Spanish Flu would require nearly 750,000 ventilators and that the US needed to develop local sources of manufacture for anti-viral medicines (DHS, 2005).

The existing inequality and imbalance in the supply chain hinders the improvement of predictability and accountability. Financially constrained buyers have found it difficult to access products, as well as information about the basic location, quality and quantity of products, in a market economy that prioritizes making a profit over other objectives, such as service level, lead time for delivery, or inventory level (Gonzalez and Jung, 2020). It calls for increased supply chain visibility with central coordination, which should likely include active management of strategic stockpiles to avoid similar obsolete and/or expired supplies by promoting inventory turnover. (Handfield et al., 2020) address 'lowest landed cost' as a decades old strategy for globalization. The irreverence for soft costs including risk analysis, the misalignment of capacity and demand across multi-echelon supply chains, the risk of aggregated demands among few suppliers, complicated by the lack of demands for many products due to reluctant economic patterns caused by containment policies is an opportunity for structural evolution of existing supply chains.

In reviewing existing literature on humanitarian supply chain and logistics management, disaster relief management, humanitarian response capacity assessment, demand forecasting and order planning, supply network assessment, and logistical operations for epidemic control, the authors found that prior to the crisis, there was an interdependence of trade and production for medical supplies. Advanced industrial countries like the United States and Germany specialized in the relatively high-tech medical devices sector, while low-cost production hubs such as China and Malaysia were leading producers of less technologically sophisticated PPE products such as face masks, surgical gloves, and medical gowns (Gereffi, 2020). The competitive advantage of country of origin is a crucial aspect for the companies that produce primarily in local districts to build competitive barriers; this makes entrance into the market impossible for foreign companies, especially in the short term (Barney 1991). In the opposite scenario, some companies develop off-shore manufacturing sites based in low-labor cost emerging economies to gain cost savings (Şen, 2008).

Starting as a health crisis, the Covid-19 pandemic is disrupting global supplies. With surging demand for ventilators and PPE, production and transportation of these critical medical supplies has become an issue of primary importance. The importance of global coordination in sourcing and allocation is increasingly recognized, but the potential to leverage the latest technologies to increase visibility and transparency into global supply chains can significantly improve the level of effectiveness with which we prevent future pandemics. This is particularly the case when considering supply chain chaos in the first two months of outbreak in the U.S. One case study of the face mask value chain in the United States shows misalignments between the priorities of U.S. federal government officials and the strategies of leading U.S. multinational producers of face masks, which resulted in exceptionally costly policy delays in terms of health outcomes. On balance, the U.S. shortage of N95 respirators during the COVID-19 pandemic is more a policy failure than a market failure (Gereffi, 2020). The rapid shutdown of the US economy led to domestic demand shocks that generated startling disruptions in the availability of everyday commodities from fresh vegetables, eggs, and milk and meat to toilet paper, with the culprit allegedly being the lack of responsiveness of hyper-efficient but rigid modern supply chains (O'Leary, 2020; O'Neil, 2020; Shih, 2020).

Without clear federal-level coordination, U.S. states, cities, and hospitals bid expensively against one another to compete for dwindling supplies. Hospital purchasing managers and state emergency management officers were frequently reported to have few options but to rely on largely unknown middlemen or unregulated factories seeking to capitalize on the booming market. Many companies exist outside the traditional medical supply chain and offer wildly varying levels of price and quality, further increasing uncertainties for hospitals and local governments to make crucial decisions (The Washington Post, March 27, 2020). Covid-19 supply chain disruptions clearly illustrate the challenge of a centrally coordinated response.

The authors found a range of outcomes in response to the disruption, as some companies have performed well through supply chain digitalization and business model innovation, while others have been devastated. Market based solutions can provide a powerful financial incentive for firms to collaborate and share data. This data is routinely produced as a by-product of supply chain activities in regular market performance. Blockchain and IoT technologies currently available allow decentralized use of supply chain data while ensuring privacy of contributing firms, nations, agencies and partners. The ability to address supply chain disconnects and bottlenecks in a near up-to-the-minute data driven environment permits integrated supply network (ISN) stakeholders to take corrective and preventative measures in an iterative and ongoing routine of production planning, supplier and service provider performance. Key Performance Indicators (KPI's) could be created considering global objectives such as time to market, service level (number of infections prevented, for example) and total system cost or stakeholder cost. While the potential incentive contribution from market-based solutions is attractive, the stakeholder complexity they add is not insignificant.

Collaboration across global supply chains can improve agility and service, reduce inventory and enable reverse logistics. Though the number of papers addressing supply chain resilience have continued to increase decade over decade, the majority of those papers address resilience characteristics specifically (plan, absorb, recover, adapt) and argue that supply chain models generally fail to represent the entire network of supply chain flows (Golan et al., 2020).

While Ivanov, et al. (2019a) offer that Track & Trace (T&T) systems combine with radio-frequency identification (RFID) and mobile devices to provide current information about process execution, a critical issue is detecting disruptions and their scope in real time. (Bearzotti et al. 2012). Embedding supply chain visualization and identification technology is crucial for this step. In addition, emerging blockchain applications in supply chains promise enhanced scale and scope of T&T systems together with creation of information pipeline systems and supply chain finance applications (Hofmann et al. 2018). The central idea is to increase visibility and efficiency based on dispersed, tamper-proof, and verifiable record-keeping in the supply chain. Applications of blockchain technology have begun to revolutionize different aspects of supply chain and operations management for development of real-time supply chain capabilities (Ivanov et al. 2019a, Kshetri 2018, Saberi et al. 2018). At the reactive stage, if a disruption happens, the contingency plans from proactive stage can be deployed faster and implemented effectively if supply chain visibility were increased." (Ivanov, et al., 2019a)

In reviewing early adoption of technological innovations, the authors find encouraging innovation in business models and collaboration mechanisms, that should yield relatively quick improvements in supply chain responsiveness, resilience, and restoration. Latest technology, like 5G, IoT, and blockchain, can aid collaboration during pandemics. Covid-19 has spurred accelerated application of technology for contact tracing to slow infection spread. One of the mainstream digital contact tracing (DCT) approaches is to use Bluetooth signals from smartphones to detect encounters with people reporting COVID-19 infection. This approach does not use location tracking or store users' location data, but if someone develops COVID-19 symptoms, an alert can be sent to others that they might have infected, with minimum intervention. Contact tracing processes do not share sensitive private information, such as identity or location, and at the same time can provide a level of actionable data at the user level, via a distributed ledger model. As to preventing spread of disease due to travel between countries, Digital Health Passports (DHP) provide a proactive prevention

measure as opposed to DCT, although successful adoption of DHP requires control of time between testing and travel, when a person can still be exposed to infection. In the case of digital certificates for travel, again inter-agency and international cooperation depends on regulatory agreement between nations, which points to the limitation of regulation in the adoption of a complete supply chain approach to tracking, prevention and remedy of COVID-19 and other similar pandemics in the past 20 years, including SARS-CoV (2003), H1N1 (2009), MERS-CoV (2012), Ebola (2014), Zika (2015) and SARS-CoV-2 (2020)(Angeloupoulos and Katos, 2020).

According to Juttner and Maklan (2011), supply chain visibility is a desired capability which may reduce the negative impacts of a supply chain disruption. Therefore, those organizations that invest in developing analytics capability are likely to also invest in visibility, because visibility provides the raw data upon which analytics systems process and operate." (Dubey, et al., 2019) A comprehensive review of existing blockchain, drone, and IoT integrated technologies and their potential can be found in (Chamola et al., 2020).

A well-cited contemporary study proposes a digitalization framework of supply-chain risk management and the authors further argue that the quality of model-based decision-making support strongly depends on the data, its completeness, fullness, validity, consistency, and timely availability. These requirements on data are of a special importance in supply chain risk management for predicting disruptions and reacting to them. Digital technology, Industry 4.0, blockchain, and real-time data analytics have a potential to achieve a new quality in decision-making support when managing severe disruptions, resilience, and the ripple effect (Ivanov et al., 2019b).

The authors find early evidence that responsiveness, resilience, and restoration can advance an organization's sustainable competitive advantage in the marketplace and as such, COVID-19 should be expected to significantly impact global supply chain network design. Global networks can promote inclusive and equitable distribution of critical supply where opportunism is mitigated. Opportunism can be revealed as product, information, financial and governance based, and can manifest as misrepresentation in the delivery capabilities, warranties, product quality (product opportunism); deceptive communication to make a situation, firm or individual look good (information opportunism); to delay payment or to distort price in order to realize benefits (financial opportunism); and coercion and manipulation (governance opportunism) (Eyaa et al., 2014). The risk of opportunism manifests in un-pre-qualified treatments and medicines that have permeated the anti-malarial drug market for anti-infectives. In 8 African countries and a study of over 200,000 public and private sector outlets, only 24% of such products were quality-controlled therapies. Likewise, the exposure of infected patients to sub-quality products can exacerbate the resistance to anti-microbial treatments. These weaknesses in existing COVID-19 treatment policies driven by individual national demands opens the supply chain for necessary medicines and equipment to abuse. For example, in one study, 96% of all overseas purchases of prescription Xanax was deemed to be counterfeit (Nayyar et al., 2019).

Applications of blockchain technology promise to improve visibility among supply chain linkages to end consumers, by allowing tracking and tracing capabilities at every value-added process along the distribution channel. Current pharmaceutical manufacturing and distribution is not ready for such a revolution (Nørfeldt et al., 2019), however many applications have been theorized, even at the individual user level in the form of a phone application (Haq and Esuka, 2018). The systemic advantages of blockchain in addressing the matter of chain of custody has proven as feasible, if not yet viable. In 2014, Maersk tracked a shipment of perishable goods from East Africa to Europe and discovered the shipment required stamps and approvals from up to 30 people, including over 200 different interactions and communications. One San Francisco firm was even able to provide evidence of a pharmaceutical blockchain solution completely compliant with the Drug Supply Chain Security Act (Scott et al., 2018).

Significant challenges remain on how to coordinate global policies while considering income inequality and varying levels of economic development. In Africa, for example, only a few countries relied on large public funds for a coronavirus response (Nigeria, Ghana, Morocco and Gambia), and

no countries initiated a payment policy, deferred tax liabilities or subsidized incomes for its citizens. In Africa, 75% of all Covid-19 relief funds were from foreign government loans and grants (primarily the World Bank and IMF), with only 25% coming from domestic sources, indicating a strong dependency on external intervention to contain pandemics in places of lower digitalization, more person-to-person transactional business, and comparatively lower economic development (Ozili, 2020).

There is also precedent to incorporate essential pharmaceutical products for COVID-19, and its subsequent evolved strains, into the same collaborative process for WHO pre-qualification. This in turn will expedite approval and remove regulatory obstacles to the delivery of essential medicines (WHO 2017); the same process can be adapted to ventilators and PPE. Designs to make shields and accessory items like mask buckles can be found in ample supply online and require only a desktop 3D printing machine (Rindfleisch, 2020).

While the number of papers addressing specifically supply chain resilience have continued to increase decade over decade, the majority of papers address resilience characteristics (plan, absorb, recover, adapt) and argue that supply chain models generally fail to represent the entire network of supply chain flows (Golan et al., 2020). Optimization as a method of control has continued to increase in popularity for modeling resilience, as well as case-based approaches. However, there exists a lack of supply chain network modeling that considers entire supply chains. Linear models are especially under-represented as the nature of linearity in modeling a network of flows lacks flexibility in adapting to interrupted flows.

Where risk management addresses the mitigation of identified risks and the active determination of both internal and external risk measures, opportunism in supply chain literature reveals the context of individual firm-advantage through self-interested acts and behaviors. Opportunism can be revealed as product, information, financial and governance based, and can manifest as misrepresentation in the delivery capabilities, warranties, product quality (product opportunism); deceptive communication to make a situation, firm or individual look good (information opportunism); to delay payment or to distort price in order to realize benefits (financial opportunism); and coercion and manipulation (governance opportunism) (Eyaa et al., 2014). Maglaras et al. (2012) present a conceptual model of opportunism drawing on Transaction Costs Theory, applied to the retailer's opportunism in the food supply chain. 45 retailers' questionable actions were explained including payment delays, threats of delisting, forcing down supply prices, and demanding unexpected payments from suppliers. Suppliers were asked to explain retailers' rationale for opportunistic behavior and the response included economic uncertainty, asymmetry of information and the supplier's dependence on big box retailers for distribution of their products. Going forward, relevant models will need to include information flows and measures of symmetry. Market-based solutions with supplier incentive to participate in sharing of information should be considered.

When considering the relationships among brokers and agents and the foreign markets where PPE and medical supplies are manufactured, we must consider the concept of guanxi (personal connection) identified as an informal sentiment of cooperation among buyers and suppliers in representing their firms, is based on the need to strategically share information and join collaboration on forecasting, production and cooperation in problem solving. However, when adversarial or competitive relationships undermine the good guanxi, firms may cease symmetric information sharing, especially regarding financial performance. Fan and Stevenson apply social capital theory in the context of opportunism in the case study of 10 Chinese manufacturers and supplement the findings in the context of signaling theory in buyer-supplier relationships (BSR's) (2018). When considering the effects of buyer-supplier relationships, the collaborative, convergent goals of BSR's contribute to the ability to identify, anticipate and mitigate risks between firms. When deciding to adopt an inter-organizational system, supply chain opportunism depends on the relative dependence of the buyer-supplier dyad to determine the likelihood of opportunistic and cooperative behaviors after system adoption, applying the finding by (Clemons and Row, 1992) that this risk is the

possibility of opportunistic behavior by another party to the relationship, leading to uncertainty surrounding the division of the benefits from the increased integration of decisions and operations (Liu et al., 2006). We observed this exact problem in the disruption of product flows by embedded intermediaries who utilized their *guanxi* to ensure their own selfish means to supply the American market. In such a buyer supplier dyad, the relationship may be either independent or interdependent; or either the buyer or the supplier maintain relative opportunistic advantage. Ex post opportunism is greatest in the buyer-power relationship where the supplier's ability to retaliate is limited by buyer control, indicating that a dyad with symmetric dependency can achieve greater benefits from an electronic data interchange (EDI) or other interorganizational systems for sharing information.

The implementation of IoT and methods of optimal strategic decision making to support a shared digitalized supply chain promise to improve these humanitarian and pandemic supply chains. Optimization as a method of control continues to increase in popularity for modeling supply chains, along with case-based approaches. More comprehensive single and multiple objective models are presented with a strategic mass balancing approach in Mohammadi et al. (2017) where operational and financial objectives are considered across supply chain echelon. Badhotiya et al. (2019) present a multi-objective mixed integer programming model formulated to consider the multi-product, multi-period, and multi-site manufacturing environment, while minimizing total cost, delivery time, and backorder level between two echelon; and (Sun et al., 2020) present an Evolutionary Network (EV) optimization considering manufacturers at the core of a heterogenous supply chain consisting not only of up and downstream partners, but also peer nodes, with the goal of testing for cascading failures due to insufficient load, as a Synthesized Supply Chain Network (SCSN) that can test the supply chain for robustness against echelon failure. These more recently developed models consider the dynamic potential of processing capacity and technology capability to support IoT and Industry 4.0 methodologies. However, the more realistic state of supply chain management is not yet so advanced in implementing these complex risk-management models. For example, a literature review on supply chain risk management by Fan and Stevenson (2018) finds 85% of papers addressed work conducted in a single country. 52% of papers addressed a single industry or industries, and 77% of papers evaluated for research perspective took the point of view of the buyer. In fact, only 5 papers in the review took the seller's perspective. In order to ensure equity among stakeholders, Optimization of entire supply chains will need to be normative.

3. Discussion

In practice, modern operations management benefits from a robust legacy of operations research, decision sciences, and systems thinking. Scholarly research, practitioner experience, and technological evolution have co-created the highly optimized organizations that today pursue their various missions. But what remains lacking, are collaborative links between firms, industries, governments, and the full spectrum of for-profit and non-profit entities and stakeholder groups. This next evolution is fully feasible now, as latest generation technologies can facilitate data transparency, while still protecting stakeholder interests. The means are in front of us to enable quick, efficient, and effective response during crises like the Covid-19 pandemic. What is lacking is a clear vision, open standards architecture, stakeholder consensus, and appropriate incentives to participate.

R. Martin Chavez, Senior director and former global head of securities, Goldman Sachs, was recently quoted saying, "I worry more about nonfinancial companies than I do about financial companies. If you looked at the pandemic, there was very little concern about the integrity and stability of banks. Think of how startling that is, right? Compare that to the financial crisis, which was all about concerns about participants in the financial ecosystem. In the current crisis, the concern has been about everybody except banks, and I would say an important reason for that is CCAR (the Federal Reserve's Comprehensive Capital Analysis and Review, an annual assessment of the largest U.S. banks). Should there be a CCAR equivalent for systemically important nonbanks? As we discovered in the pandemic, there's a lot of systemically important companies. It suddenly became obvious to everybody. Without Amazon or Google or our internet service provider, our problems

would become even greater. And so, do we want to have some kind of framework so that we can have confidence in nonfinancial companies in a crisis?" (Basak, 2021) The supply chain transparency for which the authors advocate, could provide precisely this type of risk mitigating framework during the next crisis.

The decades of experience in operations research, decision sciences, and systems thinking fully prepares organizations for this next step in collaboration. Many industries and firms have already embraced the move from MRP and ERP systems, to MRP II and CPFR. The latter—collaborative planning, forecasting, and replenishment, having been introduced over two decades ago—utilizes an open standard approach to facilitate timely, consistent intra-industry sharing of critical supply chain data. This data transparency is crucial to an organization's supply chain operating in a lean or agile fashion. Raw material suppliers need visibility to production schedules, producers need visibility to retail forecasts, 3PL's need visibility to anticipate shipments. CPFR provides industry guidelines to digitalize lean operations.

Connectivity improvements for these evolutionary systems kept pace in development. Earlier generations of these systems began with legacy hardware connections, such as analog voice lines, modems, and EDI protocols. Broadband speed, capacity, and ethernet connections, combined to provide sufficiently reliable and usable internet access. This improved connectivity fostered adoption of MRP logic for national and international organizations, in the form of ERP systems. Each improvement increased operating efficiency, usually at net reduced cost. As quality management systems were recognized and implemented, it was only logical that the benefits of ERP be extended in either direction, both upstream and downstream in the supply chain. The benefits of these developments are well documented, but competitive concerns consistently constrain collaboration and data transparency.

Confidentiality concerns around IP and competitive market data are certainly valid and understandable. It comes as no surprise that while firms will come around to sharing sensitive information with trusted supply chain partners, they are loath to risking that same competitive information spreads too far on the internet. Instead, firms invest substantial funds in managing risk around their data, protecting themselves and their customers in siloes and behind firewalls. Unfortunately, these fully appropriate precautions stand directly in the path of a next big evolution in operations management. Fortunately, we find ourselves at a nexus of enabling technologies, useful to establishing new norms of transparency, while simultaneously protecting valid interests of participating organizations.

The continual advance of processing power and speed enables exponential increases in sophistication of algorithmic encryption. Using standard commercial protocols, with distributed ledger schemes such as blockchain, we are now able to establish rules-based access for various supply chain stakeholders. We have the means to facilitate the necessary step-change in supply chain visibility that would equip agreed central coordinators to manage or mitigate risks to avoid the large disruptions we have witnessed with Covid-19. And now, 5G implementations and IoT devices are rapidly being implemented with "Industry 4.0," with this exponential increase in connectivity feeding real-time data to the cloud. Big data in its truest sense is now a reality, with organizations collecting far more information than they are able to process. AI will add more and more value, but barring significant systemic change, these new value-adds will be intraorganizational or intra-industry, at best. The authors find no real indication in literature that this necessary open standard system architecture is on the verge of introduction. Just as the internet relied on a set of protocols to deliver an open source platform for data sharing, we must seek a similar digital architecture for secure sharing of real-time supply chain data.

In order to model and empirically study robustness, resiliency, service levels, and costs during pandemics and preparedness, we must ensure that we are capturing the full spectrum of cradle-to-grave links. The diversity of third-party relationships must be acknowledged, including OEM manufacturers, active and passive back-up supply for each, and inter-industry cross-pollination. While much of the actual supply chain involves private sector entities, it is crucial that government

and non-profit entities are included, especially given they are typically the funding source. And of course, for each stratification, both domestic and foreign agents must be considered and included. In 'The New (Ab)normal', Yossi Sheffi suggests that while "blockchain will still be important 3 years from now, it's not clear it's ready for prime time." He continues however that, "digital twins will become more and more important" for supply chain simulations, such as the stress testing our global transparency could facilitate. (Sheffi, 2020)

The traditional domestic US supply chain process is currently almost entirely dependent demand driven. The private sector production and distribution on which we rely, uses Lean Operations and JIT Inventory approaches to supply products and services, as funded by government bodies and NGO organizations. There is no inherent incentive for buffer stocks of raw materials, sub-components, or back-up supply contracts, but only for fully funded finished goods. By investing in IoT devices, blockchains for secure data transfer, and cloud-based applications with latest generation IP/privacy protections, we can gain the visibility to deploy shared strategic supplies rapidly. With confidence in knowing what is available where and when, we can strategically invest in critical raw material stockpiles, sub-assemblies and components, and high priority finished goods. Furthermore, without the enhanced visibility afforded by investing in a latest generation digital backbone, the value-adds from reverse logistics of re-stocking, refurbishing, recycling, and responsible disposal are lost.

Unfortunate though it has been, the Covid-19 pandemic should serve as catalyst, to mobilize necessary investments. The pieces are here already; the technology hurdles are negligible, if at all. The internet, wireless and cellular networks, barcodes and RFID, big data and the cloud are already mature. AI, IoT, blockchain, Industry 4.0 and 5G are rapidly becoming so. Robust, secure algorithmic crypto logic is commercially available now. A timely example is TripleBlind's implementation to assuage privacy concerns, facilitating broad adoption of contact tracing mobile applications. (<https://tripleblind.ai/>) An open standard of system architecture for this step-change in supply chain transparency is one of the key final pieces. An early favorite is Provenance Chain's approach using market incentives to drive broad adoption of blockchain enabled supply chain transparency. (<https://www.theprovenancechain.com/>)

With stakeholder alignment on robust systems architecture, likely using a blockchain distributed ledger scheme, thought must be given to market incentives to encourage adoption and information sharing. One approach would be to compel participation as a condition of market entry. For example, similar to qualifying products or services for listing on the GSA Schedule, a firm desiring to sell PPE to the VA or DoD would need to provide real-time supply chain data via blockchain. As usage grows, central coordinators (such as CDC, DHS, DoD, FEMA, etc.) would be well positioned to pro-actively stress-test supply chains, just as we do with banking. With critical mass in usage, exception reporting dashboards would bring attention to risks in a timely fashion. In the midst of a pandemic, resources can be far more quickly and accurately deployed and re-allocated, as warranted. Commissioning reactive stockpiles of PPE after Covid-19, based on the assumption that they will be called for in a future pandemic, may in some cases be smart, but in all cases they will remain static inventories, isolated from central coordination, and subject to competing local demands.

4. Conclusions

During the Covid-19 outbreak, supply chain disruptions have been numerous and obvious. Frequently, those shortages include both perceived lack of control over manufacturing facilities and credible chain of custody on finished goods. As foreign production is involved, many are left to wonder why countries would so jeopardize their security. Businesses and governments frequently determine that manufacturing a component or conducting a service need not be a core competency for them. In such cases, it can make very good sense to contract with another party who has deeper expertise and perhaps greater scale. That new supply chain partner may well be within the same country or even the same facility. A persistent trend for two or more decades now has been the movement away from tactical purchasing transactions, toward strategic sourcing of long-term

supplier relationships. Firms seek to both mitigate risk from supply disruption and to unlock additional value, by forming partnerships in their supply chains, sharing information, and increasing visibility to their supply chains.

Valid strategic reasons organizations elect to outsource abound, including cost, quality, access to technology, and risk mitigation. Engaging strong suppliers in long-term relationships can be a powerful risk mitigation strategy, giving you redundant sourcing options in times of crisis. But what Covid-19 has shown many organizations is the need to rationalize their sourcing strategies and conduct thorough risk assurance, especially when critical stock is involved. Hence, it is expected that businesses and government, learning from this pandemic, will increase insourcing, self-performing again those items deemed of high risk or high impact.

Whereas outsourcing speaks of transfer of processes to another, offshoring is the practice of relocating an operation that was previously domestic, to a foreign country. The two terms are frequently confused, but they are critically different. When offshoring, a business may remain the primary owner of the assets involved, though at times joint ventures are the legal structure. For example, it is GM's design studio and factory in China; they have not outsourced production of Buicks to a Chinese company. Similar to outsourcing, there are many valid strategic reasons to move an organization's operations offshore. Doing so frequently gains access to lower cost labor, desired raw materials, or new consumer markets. But just as with outsourcing, offshoring brings its own set of risks. Covid-19 illustrated the false sense of security organizations carry when they choose to offshore their own operations, much less outsource them in a foreign country. Both businesses and governments will be actively re-assessing their supply chains for existential threats. Governments have long restricted the transfer of cutting-edge technologies with military applications and we should expect them to do the same with critical medical and food supplies going forward. That said, we should note that it is likely a limited number of nations that have the ability to make PPE at this point and most are dependent on foreign markets. For example, China was challenged to source necessary ventilator technical components from Germany and Switzerland at the onset of Covid-19, along with critical materials for N95 masks.

By definition, just as operations management is about managing the processes an organization uses to provide their goods or services, supply chain management is managing the internal and external network of entities that complete those processes to provide the goods and services. In simplest terms, supply chain management is about getting the right things, in the right quantities, to the right entities, at the right time, to the right place, all at the agreed upon quality, service, and price. The key to doing so consistently is real time visibility to the full, relevant supply chain.

In spite of efficiencies in supply and latest technologies, Covid-19 has revealed the critical national and health risks from supply chain gaps. One solution some will advocate will be massive Federal and state stockpiles of selected supplies, as part of the rise of a larger medical industrial complex. Some have envisioned each Federal, state, and local fiefdom with their own inventories of items they deem critical in an epidemic. However, we should acknowledge the tremendous cost of these redundancies and that while some of them may be warranted, many will not.

Companies will invest in visibility into their own supply chains, as they should, to manage their risks. Governments will do so, at least in the areas of supply deemed critical to life and health. The silver bullet would be to do so collaboratively. Lean operations and JIT inventory systems excel in efficiency and agility, because they rely on collaborative, trusted supply chain relationships and transparent, full disclosure of relevant information. Firms do not share sensitive sales forecast data with transactional vendors but rely instead on long-term partners. Doing so allows them to shift inventory levels back upstream in the supply chain.

In this paper, we are advocating the establishment of a real-time map of global value chains, interlocked with firms' own proprietary data, to give government administrators visibility to the status and location of available inventories. By mapping the flows of goods, in times of crisis government administrators could identify necessary resources and coordinate the quickest and most efficient deployment to areas of need. Latest generations of security protocols, utilizing blockchain

such as Provenance Chain and crypto logic such as TripleBlind, could protect firms' competitive data, while allowing government administrators to stress test supply chains, much as we do the banking sector.

Drawing on the extended literature and available early data for PPE supply in this pandemic, this study emphasizes that Covid-19 supply chain disruptions clearly illustrate lacking central coordination and contributes to the supply chain literature on the impacts of visibility as well as crisis responses. Central coordination of supply requires transparency of materials stocks and flows. Latest technology, like blockchain, IoT and 5G connectivity, can aid collaboration during pandemics and help with supply-chain risk analytics. This can improve agility and service, reduce inventory and enable reverse logistics. Improved transparency can further contribute to enhancing supply chain resilience and ripple effect control. At the same time, a transparent global network can and should allow inclusive and equitable distribution of critical supply.

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