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Sustainable Supply Chains in the Age of AI and Digitization: Research Challenges and Opportunities

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Sustainability has become a global corporate mandate with implementation impacted by two key trends. The first is recognition that global supply chains have a profound impact on sustainability which requires "greening" the entire supply chain. The second is technology—digitization, artificial intelligence (AI), and "big data"—which have become ubiquitous. These technologies are impacting every aspect of how companies organize and manage their supply chains and have a powerful impact on sustainability. In this essay, we synthesize current dominant themes in research on sustainable supply chains in the age of digitization. We also highlight potential new research opportunities and challenges and showcase the papers in our STF.

Keywords: sustainability; supply chain management; artificial intelligence; digitization; big data

INTRODUCTION

Sustainability has become a global corporate mandate. Accepted practice of sustainable business calls for measures of business success that include social, economic, and environmental factors; and stewardship of resources that create lasting value and opportunity from one generation to the next (Sanders and Wood 2019). Achieving sustainability, however, has been impacted by the convergence of two prevailing trends. The first is the dominance of global supply chains and their profound impact on sustainability (Carter and Washispack 2018). The truth is that the vast majority of adverse impacts, whether environmental, economic, or social, come not from direct operations but rather from end-to-end supply chain activities required for sourcing, production, distribution, and logistics. For example, issues such as electronic waste, greenhouse gas emissions, sourcing of conflict minerals, or human trafficking arise in the context of supply chain management and must be addressed within that domain, not simply in the context of marketing or operations.

Where once supply chains focused on delivery, today's supply chains are designed to support customer-centric business models. Global supply chains are seen as strategic assets, capabilities, and sources of competitive advantage (Min et al. 2019). This is forcing managers at all levels to re-evaluate how they view, manage, deploy, design/redesign, and measure supply chain performance. Sustainability has become a critical part of that evaluative process. Authentic sustainability requires greening the entire supply chain. It also requires transparency with respect to secondary and even tertiary partners regarding social and environmental performance.

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The second megatrend impacting attainment of corporate sustainability comes from technology in the forms of digitization, artificial intelligence (AI), big data, and robotics applications. Digital applications are affecting every industry and all supply chains (Bell and Griffis 2011; Klumpp and Zijm 2019). Data-driven technologies and software-managed processes (henceforth "digital" platforms) such as social media, mobile, analytics, embedded devices, distributed and additive manufacturing, and the like hold significant promise for enhancing the mission of corporate sustainability. The growth of the Internet, social media, and web-centric software has interconnected customers and firms selling to them; and suppliers with the firms who are making products or delivering services. However, the challenge for both researchers and practitioners is to determine how to leverage these technologies and the enormous amounts of data they generate for performance measurement and transparency; effectively integrating the capabilities of digital platforms into supply chain sustainability decisions; and to develop innovative tools, techniques, and models that can leverage these technologies to unlock value (Waller and Fawcett 2013, 2014).

The term "big data" underlays these technologies and has dominated both the popular and academic press in recent past. An excellent definition of "big data" is offered by Maniyaka et al. (2017) who define big data as datasets whose size is so large that the quantity can no longer fit into the memory that computers use for processing. We define the term "big data" in its most generic form: data sets that are large ("volume"); that is collected in near real-time (high "velocity"); present in myriad forms ("variety"); and at various levels of trust ("veracity") (McAfee et al. 2012).

Three trends have fueled the Big Data revolution in the supply chain. *First*, there has been an explosion of data available *within* the company and *outside* the company in the public domain. In addition to the data generated by traditional transaction-based enterprise systems (POS, RFID, ERP, etc.), supply chain planners now have access to vast amounts of data generated from unstructured data sources such as digital clickstreams, camera and surveillance footage, imagery, social media postings, blog/wiki entries, and forum discussions. *Second*, supply chains today are heavily instrumented—sensors, tags, trackers, and other smart devices are collecting data in real time on a wide variety of business processes. Gartner estimates that by 2020, there will be around 26 billion such devices in the supply chain monitoring and connecting supply chain operations—from supplier operations, manufacturing, to distribution and point of sale. *Third,* advances in computing architecture such as cluster computing and cloud computing have enabled the storage, retrieval, analysis, sharing, and distribution of data and insights easier and cheaper.

We use the term *big data analytics*—a set of scalable methods and tools—that can extract meaningful insights from these big datasets, prescribe solutions, and predict the future (Sanders 2018). The added premise is that as researchers, we can build better models and develop and refine underlying theories in the presence of this abundance of data. We use the term *digitization* to mean converting all this information into a digital format.

What does this mean for sustainable supply chains? First, new and interesting insights about the customer and the supply chain are now available from these large datasets and digitized information. Second, it opens up new avenues of exploration in supply chain management. Both these trends help in making the supply chain more efficient and transparent, a key requirement for a sustainable supply chain. Finally, it has the potential to solve large-scale multidisciplinary problems considered intractable in the past.

The purpose of this Special Topics Forum Issue is to stimulate research at the nexus between digitization and the needs to manage truly sustainable end-to-end supply chains. We welcomed a wide variety of topics spanning multiple industries that address issues that leverage digitally driven technologies and the copious data they generate to drive sustainable supply chains. The focus was not on the technology per se, but how that technology can transform how we think about and manage sustainability issues. This is an emerging area, and papers representing a true nexus are few. We showcase two papers that represent this work.

Also, as preparation for this Special Issue, all of us spent a considerable amount of time over the last two years communicating with data science and technology leaders, academic colleagues, and policymakers. From these discussions, we synthesize current dominant themes in big data applications and present them in the next section. We then highlight potential new research streams that big data can unlock and summarize the papers in our STF. We then offer our concluding thoughts in the last section.

DOMINANT THEMES

The potential to develop a better understanding of the environmental and social impacts of supply chains has escalated with the advent of big data and digitization. Big data has created an unprecedented opportunity for improvement along all the dimensions of sustainability. At the same time, as we will discuss, big data also creates a host of unknown environmental and social challenges. As digital technologies become more widely adopted and reach sufficient scale, they will have wide-reaching impacts, especially on decisions regarding sustainable supply chains.

Consider a loose definition of sustainability as making decisions while simultaneously taking into account economic, environmental, and social considerations (Corbett 2018). Defined in this manner, it becomes evident that sustainability is intertwined with big datasets as they are the foundation of decision making in the digital era. In the quest to measure the performance of these decisions with regard to their environmental and social impact, especially as they pertain to supply chain decisions, an explosion of data erupts in variety, volume, and veracity.

There is widespread recognition that big data and digitization applications are "disruptive and important" (O'Marah and Chen 2016). Firms are also making significant investments in big data storage and applications across a range of decisions[1]. In sustainability, for example, in the past, companies received periodic updates on climate conditions, carbon emissions, or the treatment of workers at supplier facilities. Digitization and technology have now created a different environment where these types of phenomena are monitored in real time with data generated continuously at a high level of granularity meeting the definition of big data, with volume, velocity, and veracity. Satellite images monitor and generate data, social media posts report on worker conditions, and RFID tags monitor product integrity and movement.

The big data applications across the supply chain, however, are fragmented and idiosyncratic to the firm and industry (Sanders 2016). This is particularly true along the dimensions of sustainability that address the breadth of economic, social, and environmental factors. The interest is broad and includes such varied topics as monitoring of greenhouse gas emissions, global climate health of watersheds, human health, biodiversity, value chain impact, social impact on workers, and many others. The areas of interest are extremely diverse. However, we summarize some of the dominant themes in these applications across four broad supply chain functions: Demand Management, Manufacturing & Operations, Transportation, and Sourcing. Our classification is borne out of convenience—the applications are not meant to be exhaustive and many of the applications span multiple boundaries as is the case with this topic. These are also the common themes and topics that have consistently dominated logistics research over the past decades (Goldsby et al. 2019).

DEMAND MANAGEMENT

An explosion of data is now available as the customer moves through every stage of her decision journey. Customer clickstreams, social media interactions, or Google searchers inform how customers discover and evaluate products. In-store technologies such as beacons, tags, virtual rails, and engagement kiosks track buying behavior of individual customers. Modern

[1]The number of RFID tags sold globally is projected to rise from 12 million in 2011 to 209 billion in 2021 (Maniyaka et al. 2017). Internet of Things (IoT) investment in production is expected to double from $35 billion to $71 billion by 2020 (AT Kearney (2017)). Further, the robotic sector is projected to grow to over $137.4B by 2020.

transactional systems not only track sales in real time but are connected to inventory and customer databases across multiple channels. Finally, technologies are enabling the rise of the "omni-channel" experience—consumers can now seamlessly move between channels as they evaluate, purchase, return, or seek help with products and services (Gu and Tayi 2017).

Such fine-grained data have enabled *real-time personalization*. Based on the customer attributes which could include demographics, location, or browsing history, products, offers, and prices can be personalized and "pushed" to the customer. At a more aggregate level, *customer micro-segmentation* can offer small sets of customers tailored products and incentives. The retailer Neiman Marcus, for example, uses behavioral segmentation matched with a multitier membership rewards program (Kiron et al. 2013) to identify top-spending customers. Purchase incentives are tailored specifically for them, resulting in significantly higher margin purchases.

Pricing decisions can now be made in near real time using a variety of new data sources—competitor pricing, demand and supply economics, and customer characteristics (Fisher et al. 2018; Simchi-Levi 2017). Uber, for example, uses "surge" pricing based on demand characteristics. Kroger, a large US grocer, is experimenting with electronic shelf edges[2] that can personalize prices for individual customers.

Big data tools are also *improving demand forecasts*. Near real-time tracking of inventory and customer buying patterns has made it possible to project sales (or estimate demand) more accurately than before. When a stock out occurs, for example, demand is "truncated" but real-time tracking of consumer buying patterns can close this gap. User-generated content from social media and Google searchers can now be incorporated into product forecasts. Cui et al. (2018) use the quantity and quality of Facebook comments to improve forecast errors, while Boone et al. (2018) use consumer searchers on Google to improve product forecasts.

These examples impact sustainable supply chains indirectly. Promotions are more efficient; the right products are stocked in the right quantities at the right times; forecasts are more accurate—all improving efficiency in forecasting and replenishment of products and services.

MANUFACTURING & OPERATIONS

Sensors and connected applications are able to generate significant amounts of data about processes in near real time. This has given the ability to design *better processes* and *monitor* and *react* to any changes quicker to increase quality and productivity. This enables better measurement and building sustainability into these processes. Second, these big data streams are enabling scale solutions, helping firms tease out *enterprise-wide insights* from the data. Following are some specific examples.

Labor environment

Firms are increasingly interested in better understanding labor conditions of workers in facilities across their supply chains. In the past, these measures were gathered by randomly sending auditors to factories and warehouses for periodic assessment. The goal was to gather data on environmental and social conditions from these random visits.

Today, companies across multiple industries have codes of conduct for suppliers that span working conditions and quality of life of their employees. Connected sensors and devices also monitor important sustainability metrics such as resource usage and emissions. Sensors can also continuously monitor and stream visual and other data to the parent company. Workers are empowered to use their smartphone devices to record working conditions and hazards and then share that information globally. Some companies are taking the opportunity to showcase their support for working conditions. For example, global retailers such as Marks & Spencer, Walmart, and Adidas are directly and confidentially contacting individual workers in their suppliers' factories to get a feel for working conditions and human rights.[3] For many of these companies, it is an issue of leading on sustainability by directly monitoring suppliers' working conditions.

3D Printing

Big data is also accelerating innovations in the physical world making it easier to mass produce yet personalize products. 3D printing or additive manufacturing is one such technology. It brings the promise of manufacturing products sustainably by enabling quick and rapid prototyping often using recyclable materials, producing near-zero waste streams, and ability to machine complex and more efficient geometries. On the other hand, it is unclear if it has an advantage over traditional manufacturing methods (see Corbett's (2018) discussion on 3D printing). The energy requirements for 3D printing depend heavily on the materials used. Certain plastics, for example, use a significantly large amount of energy (compared to conventional manufacturing) and leave behind a "cloud" of nanoparticles. However, new developments in thermoset plastics and microwelding technologies and the growing infrastructure to support distributed manufacturing (local maker spaces and fab laboratories making products on demand from distributed designs) make 3D printing a potential game changer in the foreseeable future.

3D printing poses a significant potential impact on the physical world (Corbett 2018) by changing traditional plant setups, supply chain structures, reductions in long-distance transport and leading to customer-centric plants that focus on local demand. Some manufacturers are preparing their ecosystems for changes that may be coming as a result of this technology (Bromberger and Kelly 2017).

[2]https://www.wsj.com/articles/at-kroger-technology-is-changing-the-grocery-store-shopping-experience-1487646362 Accessed December 7, 2017. See related YouTube video: https://www.youtube.com/watch?v=w2vvcz-fki4 Accessed December 7, 2017.

[3]//economictimes.indiatimes.com/articleshow/27152368.cms?utm_source=contentofinterest&utm_medium=text&utm_campaign=cppst

Anthropomorphic robots

Another innovation enabled by big data is smart sensing robots that can work alongside humans. Cameras, sensors, and anthropomorphic features (like the human hand, or the ability to show emotion) make a robot more able to sense and respond to its environment. For example, Amazon uses robots to move products in their fulfillment centers. Rather than human pickers walking the aisles to pick orders, these robots "pick up" the shelf and bring it (managing robot traffic on the way!) to the packers who then start assembling the order. This significantly improves the productivity and safety performance of the fulfillment center. Such robotic fulfillment systems also enable "dark" warehouses—buildings can be climate controlled and lighted only where there are humans—saving money and reducing resource usage. Such robotic systems are also now commonly used in typical pallet- and case-based distribution centers—retailers such as Target, Walmart, Kroger are all experimenting[4] with robots that can load and unload pallets to and from a stocking location.

Human-like "smart" robots[5] also work alongside humans in the manufacturing process. They can be trained to do tasks that are deemed unsafe (like feeding metal sheets to a stamping machine) or too repetitive. Efforts are underway to make these robots more anthropomorphic (like Mr. Data of Star Trek) so they can be highly productive yet pleasing to work with humans around them. Such visions of a robotic future often usher in dystopian nightmares—of machines enslaving humans or relegating them to a "Matrix[6]." Yes, they do bring serious challenges to policymakers—unemployment and the future in a knowledge economy—but we remain optimistic that such intelligent robots will make supply chains more efficient and sustainable.

TRANSPORTATION

Sensors in the transport system (cameras, telemetry detectors, automated toll booths, etc.) combined with location and telemetry data of vehicles have enabled the visualization and *real-time usage* of transport networks. Google Maps is one such example in the road network—anybody with a cell phone can get navigation and traffic information and trip times. A second layer is the addition of user-generated content to traffic and navigation data—the Waze App (also a Google product) lets users populate it with real-time traffic incidents. Such applications are of great use to transport planners for designing networks that minimize congestion.

Second, both freight and personal vehicles are equipped with a variety of sensors—cameras, GPS, etc.—that analyze real-time data on vehicle performance and the surrounding environment to avoid or minimize potentially dangerous situations. This has the potential to *increase the safety and efficiency* in the transport network. These technologies also enable autonomous driving vehicles and drones. Third, sensors on shipping containers, box cars, tractor trailers are not only able to give location information to *track* freight, they also ensure *security* the freight while in transit. Finally, data from mobile devices and GPS sensors in vehicles are able to link location and trajectory data to individuals using the transport network giving rise to the *sharing economy* (likes of Uber and Lyft. See Cohen (2018), Section 3.1).

Autonomous driving vehicles/Drones

One area where newer data-driven technologies are spilling over into the physical transportation world is in the arena of autonomous driving vehicles (ADVs) both for personal and for commercial use. The US Department of Transportation defines self-driving vehicles as "vehicles in which operation occurs without direct driver input to control the steering, acceleration, and braking and are designed so that the driver is not expected to constantly monitor the roadway while operating in self driving mode." (U.S. DOT, see https://transportation.gov/av)

Every major company in the transportation sector is significantly investing in this technology. Uber recently signed a deal with Volvo for 24000 self-driving vehicles[7] , betting on the benefits of this technology. Line-haul trucking is slowly but inevitably moving toward autonomous driving. Autonomous technology producer Embark, in partnership with Ryder logistics, is running "the longest autonomous freight route" moving Electrolux appliances 650 miles between California and Texas. While Ryder drivers drove off-highway segments, autonomous technology takes control of the trucks on highway segments[8].

The advantages of ADVs are many. First, ADVs bring the promise of cutting the cost of labor by driving more hours and using fewer drivers. Second, significant savings can be made on fuel efficiency by running trucks in a platoon. Finally, ATVs also promise increased safety. On the other hand, it has the potential to inflict serious economic and social costs. Truck drivers will lose jobs and truck stops may go out of business. Second, ADVs do not have widespread acceptance in the public realm. Third, regulatory frameworks are still catching up to this technology (who to blame if there is an accident?).

Drones are yet another data-driven innovation to spill over to the physical world. They are being widely used in supply chain inventory and asset monitoring, inspection, and quality control of physical supply chain infrastructure. They are also heavily used in disaster management, to survey and deliver essential supplies. When Hurricane Irma hit Houston, insurance companies were able to use quickly use drones to access damage and make insurance payments. Second, drones are now being used to make routine deliveries—DHL, for example, makes routine medical deliveries to islands in the North Sea.

Third, the greatest potential of drones may be the "last mile" delivery of small packages. If and when the much-publicized Amazon Prime Air goes into operation, Amazon anticipates 30-min delivery times for parcels up to 5 lbs. over 10 miles (Eadicicco 2016). Amazon estimates that the cost to

[4] https://www.wsj.com/articles/fully-autonomous-robots-the-warehouse-workers-of-the-near-future-1474383024

[5] See for example the Baxter robot from Rethink Robotics

[6] https://www.warnerbros.com/matrix

[7] https://www.nytimes.com/2017/11/20/technology/uber-deal-volvo-self-driving-cars-.html Accessed December 8, 2017.

[8] https://www.youtube.com/watch?v=3yPMxV11KaA Accessed December 8, 2017.

move a five-pound package less than 10 miles will be only $1, far less than any current conventional delivery method (Keeney 2015). Regulatory restrictions, safety and privacy concerns, and the public's skepticism are primary barriers to its widespread implementation.

SOURCING

New technologies are impacting sourcing in four important ways. First, technologies are able to leverage data to present an integrated picture of the "spend" enabling firms to *optimize contracts*. Second, supply chains are becoming more *transparent*—it is becoming easier to track the environmental, social, and economic performance of suppliers. This has significantly improved *risk management*. Third, ubiquitous sensing technology is enabling the *tracking and tracing* of products improving efficiency and safety. Finally, collaborative planning technologies (such as CPFR) are removing the old stumbling blocks of poor information availability improving customer service (see Piluso et al. 2016 for the emerging landscape in procurement)

Blockchains

One major technology on the horizon is the "Blockchain," that was originally conceived as a mechanism to track and secure bitcoin transactions[9] . A Blockchain is a distributed ledger, or book of transactions, made out of a growing list of records or "blocks" linked and secured cryptographically. Rather than having one record in one location, it is a record shared among computers all around the world. The "blocks" are electronically linked with a timestamp and transaction date. Once transactions are recorded in any block, they cannot be retroactively altered without altering all the subsequent blocks. This makes transactions verifiable and inherently difficult to modify. This also makes transactions via Blockchains safe, fast, and automated. Built into Blockchains is a consensus mechanism that allows anyone to transact and conduct business with each other without having to go through a third party. As such, Blockchains create huge opportunities to significantly cut transaction costs and change the nature of transactions in every industry, by making them efficient, transparent, and thus sustainable.

Given that supply chains are networks of entities that transact with one another, Blockchains have the potential to transform supply chain transactions especially in transportation and purchasing. Due to distributed ledgers, settlement times will be instantaneous. Furthermore, Blockchains *could* eliminate the need for third parties such as financial institutions and even some 3PLs using "smart contracts."

[9]See the IEEE Spectrum special report of Bitcoins. It explains how Bitcoins works and their potential to transform transactions: https://spectrum.ieee.org/static/special-report-blockchain-world Assessed December 8, 2017.

NEW RESEARCH OPPORTUNITIES

New opportunities to leverage data

Data calibration

As the capability to analyze rich data sets become available to researchers, it opens up a set of new questions. The questions are not specific to sustainability but are vital to making decisions that directly impact it: What is the best strategy to acquire data? Was the data collected properly? Does the data represent what we want? Does the data have the adequate signal we are trying to measure? Collectively, we call it *Data Calibration* but more conventionally, this is the separation of the proverbial signal from the noise.

Researchers in the life sciences, medicine, and engineering, for example, have well-established standards and protocols on collecting and calibrating large datasets. Astronomers when photographing deep space objects typically use CCD cameras on telescopes and use long exposures to capture the "signal" or photons coming from these objects. Unfortunately, they also have to contend with light pollution, the "noise" originating from the CCD camera's sensor and circuitry, clouds, airplane trails, etc. Standard protocols call for taking multiple exposures of the object (called "lights") and "stack" them to boost the signal. Exposures for the same length are taken with the camera shutter closed called "darks" and the camera pointed to an evenly illuminated white light (called "flats") to capture camera noise. The darks and flats are then "subtracted" from the lights to provide a cleaner signal. Light pollution and other artifacts are also calibrated and subtracted from the stacked image yielding beautiful pictures of deep-sky objects several thousand light years away.

The design of such data acquisition and processing strategies opens up a viable area of research for the supply chain community. For example, if we are trying to analyze retail flows into a shopping mall, we can triangulate and use multiple sources—mobile phone data, social media interactions, surveys, etc. (see, e.g., Lovelace et al. 2016) to determine how customers flow in and out of an area. The data sources can be cross-validated and filters established to determine how best to assemble a high "signal" dataset with the least "noise" of these flows. On a smaller scale, if one wants to measure customer engagement across social media platforms, it is important to filter out spam, bot-generated content, "fake" content—a process that is grounded in theory—to get an accurate picture of engagement which can then be used for prediction.

Large datasets also not immune from the typical problems faced by "small" data—one of bias and representation in datasets. The *device* collecting the data and *how* data is collected, for example, can introduce bias into the data. In a now-famous example (see also Boone et al. (2019)), the City of Boston used the "Street Bump" App as an initiative to collect data on potholes. A resident's phone (via the accelerometer) would automatically detect potholes while they are driving which the city could then repair. The App reported disproportionate number of potholes in wealthier parts of the city where residents owned smart phones and cars. Such worthy programs too can unconsciously build in bias—against the most vulnerable segments (the smart phone ownership was the lowest among old and poor people) of our society.

We also note that in the rush to collect and exploit big data, information contained in "small" data sets can be left out. As Corbett (2018) notes, we must also ask what is *not* being captured. For example, volunteered "big" data can often be mis-representative if not calibrated. Figure 1a shows data (The idea came from the ITF 2015 report who perform a similar analysis of Copenhagen Bicycle paths) from the cycling app Strava[10] on how cyclists in Washington DC use public roads and designated bike trails. The bicycling infrastructure—from Google Maps—in Figure 1b. Such data are invaluable for public policy and the local transportation departments who can use it to plan bicycle-commuting infrastructure as cities strive to be more sustainable. However, the data do not tell us what proportion of Strava users are commuters. Second, those that populate data into Strava are more likely avid cyclists not the average commuter. Figure 1c shows census data on commuting collected via "physical" surveys mailed to residents. Strava data seem to underrepresent city neighborhoods that have high rates of bicycle commuters[11].

Boone et al. (2019), Lee (2018), and Corbett (2018) point to such "big data hubris," the "often implicit assumption that big data are a substitute for, rather than a supplement to, traditional data collection and analysis" (Lazer et al. 2014, p. 1203).

Opportunities to leverage data for prediction

Much of the applications described in Section 2 are by no means mature—ample opportunities exist for the supply chain community to develop and refine such applications. One avenue for researchers is to use newly available data from disparate sources to enhance the prediction of existing models. Reliability theory, for example, can be used to predict machine failure. Modern sensors can detect changes of small magnitude in variables of interest that were undetectable in the past—say vibration frequency of an engine, or a gradual increase in the heat of an engine. These variables measured in near real-time can increase the precision of the prediction of machine failure. A viable research stream would be to understand how patterns in the measured variables impact outcomes or prediction. For example, what observed patterns in vibration or heat would result in a failure? And why? This research stream has several applications relating to sustainability—on how to calibrate machines to reduce emissions, better transport management to conserve fuel, etc.

A second avenue is to detect patterns and associations ("Data Mining" or "Pattern Recognition" or "Lead scoring") in the data that have predictive value. Often these techniques are used in trend projection (forecasting), fraud detection (deviation from the trend), association rule learning (recommendation engines, market basket analysis, etc.), and customer segmentation.

A viable avenue of scientific inquiry would be to present the trend or correlation and explain the mechanism (*why* we see the patterns we see) behind these correlations or patterns. This is certainly a controversial issue—one might argue that actionable insights do not require an explanation but add value. In Boone et al. (2018), we were trying to predict sales of this product that was often eaten as an appetizer that was of Italian/French origin. In addition to using historical data, we used the Google searchers for the term "Antipasto" and "Hors d'Oeuvres" to help improve forecasts—the idea was that people searching those terms have an intent to purchase. Interestingly, another search term "Paradigm speakers" improved forecast errors as much as the two terms we chose. That had our heads scratching—was it a spurious correlation? Did it make any sense that people searching for a premium speaker also bought these appetizers? In our case, we validated the use of the terms we did with the help of the business owner with deep domain knowledge and by polling the customers to confirm search pathways to the purchase. It does make us wonder, however, if we are ignoring less intuitive paths of inquiry which potentially could lead to scientific progress.

Theory testing

The scientific method is built around testable hypotheses. Scientists in every discipline, including supply chain management, build models to explain the world around them. The models are then tested, and observations and experiments either corroborate or falsify these models[12]. In fact, some of the best theories start with sparse data. Einstein's general theory of relativity, for example, predicted the bending of light by the gravity of the Sun. It took an expedition by Sir Frank Dyson and Sir Arthur Eddington during the eclipse of 1919 to validate this prediction (Dyson et al. 1920).

Large datasets and digitization are challenging this very notion of the scientific method by turning it on its head. The reductionist view[13] of big data is that the abundance of real-time data mimics real life and thus the scientist is freed from any underlying theories or models. This journal and indeed others in our field would find that notion radical—however, it does open up an avenue of research. We now can use this torrent of data to challenge supply chain models in particular and management theories in general. We can "ask questions" and empirically test them, often in real time (A/B testing is one such method). The research value will be in the question asked and how insights derived can inform theory.

For example, one of us (Ram) was working with an online retailer to help understand why customers were abandoning their cart when they discovered the shipping cost. The item, an exclusive food item, costs in excess of $1,000, while shipping was about $100. The initial explanation was that the cost of shipping was too high (the item had to be cold-packed). We decided on a small experiment in parallel—to offer free shipping but up the cost of the product to $1100 (i.e., same landed cost). Turns out customers had no problem with this! Our follow-up with the

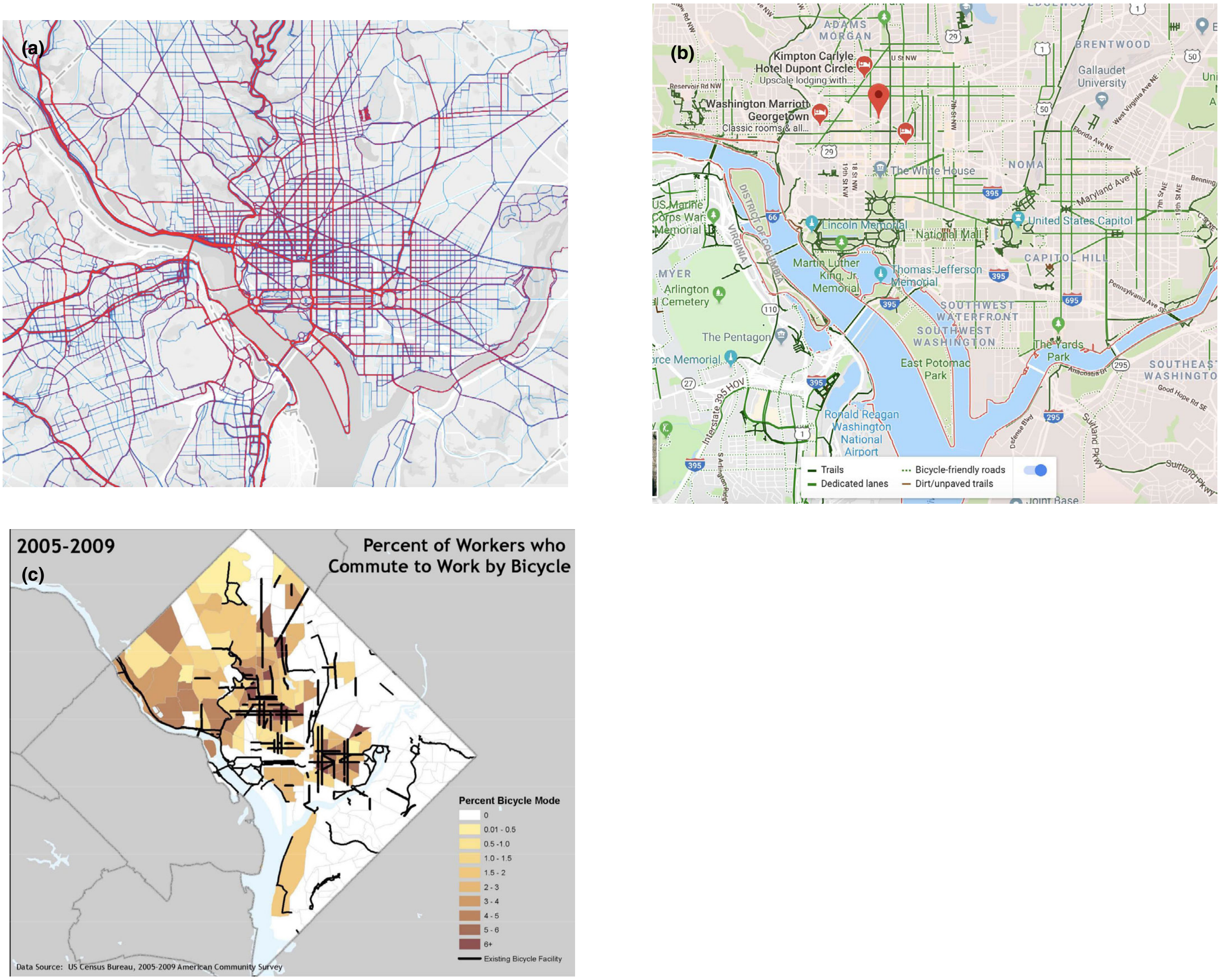
[10]This is a project of Strava Labs called StravaMetro and measures the volume of traffic captured by mobile devices (phones, smart watches, etc.). Strava does caution that these heatmaps are a tool to visualize bike traffic and not a public policy tool.

[11]Strava has since fixed this to allow users to indicate if they are commuting or recreationally riding.

[12]This is of course Sir Karl Popper's empirical falsification (Popper 1934). Falsification itself has its critics, especially in the big data era, where there is a blurring line between theory and empiricism. Also see Lakatos and Musgrave (1965) for various nuanced explanations of the growth of knowledge, especially reconciling Karl Popper with Thomas Kuhn.

[13]https://www.wired.com/2008/06/pb-theory/

Figure 1: (a) Strava metro bicycle traffic “heat map”. (b) Google bicycling map. (c) Commuting information form census data.



customers suggested that having to pay for shipping was perceived as a lack of service for the premium product. Our proposition that “the shipping cost were high”—while intuitive—was not substantiated by the data. Such tests can inform pricing and consumer behavior theory. Similar tests can be performed to test conventional theories that support sustainable supply chains—local vs. off-shored manufacturing; mode of transport traded off with inventory; buying versus generating electricity, etc.

The data, at the other extreme, let the researcher posit theories or explanations that are seemingly inconsistent (like our “paradigm speaker” correlation) with the corpus of knowledge (Feyerabend 2010;[14], 4 ed.) but has high predictive value. This does create a quandary—it blurs the line between pure empiricism and theory building. As a community of scientists, we have to address the boundaries of what constitutes “rigor” and “science” (also see the discussion on correlation versus causality in Agarwal and Dhar (2014) Editorial to the Special Issue of *Information System Research* on Big Data issues).

Privacy, bias, and ethics

As editors of this STF, it is easy to assume that we are technology and data evangelists. We are certainly believers in its enormous transformative power—however, we are also wary of the responsibility it brings on the research community.

Ubiquitous transactional, sensing, and tracking data, including mobile phone data, are collecting unprecedented amounts of information on customers. What data should we collect? How to safeguard this information? How to react to data breaches? Are all questions worth pursuing. Data collection is often not purpose-tied nor is it easy to anonymize. Recent breaches in

[14] Feyerabend famously said “Anything Goes” in his book *The Against Method*—he was against pinning the scientist down to just conventional methods of scientific inquiry. We are not advocating a wild west

Equifax, Yahoo, Ashley Madison, and Target show that customers, firms, and their supply chains are vulnerable to such hacks in the data. Federal and local laws, appropriate governance structures, credentialing and audits are all part of the solution and as data scientists we need to stay engaged in this debate.

Cathy O'Neill who has written the best-selling book on the "*Weapons of Math Destruction*" (O'Neil (2016) WMD she calls them)—on how machine-learning algorithms can build bias and discrimination into outcomes gives a scathing review of how academia is not educating policymakers of such biases (O'Neil 2017): "…academics have been asleep at the wheel, leaving the responsibility for this education to well-paid lobbyists and employees who've abandoned the academy."

While we may not agree with her criticism, her call for action is worthy of consideration. Her book is full of excellent cases on bias and inequity and often such biases work against the most vulnerable (such as the disabled, poor, or minority populations) in the society. There is another pernicious way such machine algorithms fail—failure to detect misinformation or "fake news," especially in social media platforms. The speed at which fake news stories are distributed across algorithmically curated social media platforms has negatively impacted user perception and interpretation of factual information. There is now a recognition that fake Facebook stories played an important role in the 2016 US Presidential election. After the Indian Government went through demonetization, there was a fake news story (we ourselves were recipients!) on WhatsApp that the new bank notes had "nano-GPS" chips[15] that would track these notes. The riot resulted as citizens were unhappy with the notion of the Government tracking them before the story could be debunked. This had the potential to go really bad since India has over 160 million WhatsApp users.

O'Neill goes on to say in her *New York Times* Op-ed "It's absolutely within the abilities of academic research to study such examples and to push against the most obvious statistical, ethical or constitutional failures and dedicate serious intellectual energy to finding solutions. And whereas professional technologists working at private companies are not in a position to critique their own work, academics theoretically enjoy much more freedom of inquiry."

It is indeed true that those of us who work closely with industry profess a conflict of interest—firms grant us access to data, fund pedagogic and research programs, and hire our students. Second, in many our programs and courses, the focus is more on developing the algorithm and outcomes for the focal user and not on potential ethical value of algorithms. This is slowly changing and multiple attempts to address algorithmic accountability are emerging—like the Fairness Accountability and Transparency in Machine Learning (FAT/ML) community. FAT/ML is a multidisciplinary group of researchers from the life sciences, the sociology of science, the history and philosophy of science, sociology, applied ethics, law, and computer science who have laid out a set of principles to "help developers and product managers design and implement algorithmic systems in publicly accountable ways.[16]." As teachers, reviewers, and editors, we need to demand that the algorithmic methods meet FAT/ML-like guidelines to keep them free of unintentional bias and discrimination.

INTERDISCIPLINARY RESEARCH

Contemporary supply chain management problems, central to large-scale organizational and societal challenges, are vastly more complex than those seen in the past. This is particularly true as it relates to sustainability. These problems involve large and complex supply chain networks and interdependent socioeconomic systems, involved in operating sustainable energy networks, or innovating for global value creation and delivery, or responding to global disruption. A meaningful study of climate change interventions, for example, would require involvement of meteorologists, geologists, chemists, economists, and sociologists, among others. Similarly, the scope and scale of supply chain issues involved in the task of feeding a growing population intertwine agriculture, ecology, transportation, among others.

Particularly, vexing is so-called "wicked problems," difficult to solve due to their complexity (Churchman 1967; Rittel and Webber 1973). Examples include the study of climate change mitigation, healthcare delivery, responding to human disasters, and solving water crises around the world. Wicked problems are sets of system where a solution cannot be explained by considering each of its parts in isolation (Ketter et al. 2016). Ketter et al. (2016) argue that this paradigm of the past needs to be replaced with interdisciplinary communities that jointly develop problem definitions, have a shared vocabulary, and identified research questions deemed important. Ketter et al. (2016) propose an interdisciplinary approach to address challenges of large-scale societal problems. This approach involves interdisciplinary collaboration that uses large data sets, relies on multiple methodologies, and encourages research team competitions that iteratively evolve the problem. Although most supply chain problems do not fit the definitional criterion of "wicked problems," they nevertheless encompass substantial complexities that are beyond the scope of one narrow discipline. Rather, interdisciplinary research that provides differing, and sometimes contrarian, viewpoints is needed for the development of new insights and ideas, and thus meaningful solutions.

Addressing these challenges has been difficult in the past as these solutions require holistic and comprehensive analyses based on broad data sets (Sanders and Wagner 2011). Access to big data and associated technologies has now enabled this method of inquiry. Experts from different disciplines can work from large data sets that, for example, simultaneously include patterns of usage from customers, production patterns from producers, product availability from suppliers, as well as data on public policy and regulatory constraints. Big data technologies have the potential t*o enable* interdisciplinary research.

Challenges in implementation remain. Important requirements are a common definition of the research problem, a shared

[15] https://www.thememo.com/2017/02/13/whatsapp-india-fake-news-crisis-is-leading-to-riots-bloodshed/ Accessed December 7, 2017.

[16] https://www.fatml.org/resources/principles-for-accountable-algorithms, accessed December 7, 2017.

vocabulary used to describe the problem, and the import questions researchers are asking (Rittel and Webber 1973; Ketter et al. 2016). Research suggests that disciplines with a "reasonable distance" between their centroid philosophies in theory and method may be most promising for integrated work (Ettlie and Sanders 2017). Sufficient topical and methodological overlap is needed to provide "common ground" yet too much may likely not yield accelerated outcomes due to duplication of knowledge (Ettlie and Sanders 2017; Sanders et al. 2013).

The area of forecasting has been particularly impacted by technologies. Current research in forecasting exemplifies interdisciplinary opportunities that bring together operations management and organizational behavior. Even with the availability of fine-grained information, a large number of forecasts in practice still rely on human judgment (Lawrence et al. 2006). Forecasts continue to be produced as a combination of a data-based statistical forecast and judgment (Davydenko and Fildes 2013; Seifert et al. 2015), illustrating that ultimately organizational decisions are made by the interface of technology and the human decision maker. This practice remains unabated despite ample empirical evidence suggesting that such a practice may deteriorate forecast accuracy due to a myriad of cognitive biases inherent in human judgment (Tversky and Kahneman 1974).

Interdisciplinary research has been attempting to address these issues. For example, Moritz et al. (2014) analyzed how differences in the abilities of individual decision makers, as measured by a cognitive reflection test, affect forecast performance. Similarly, Narayanan and Moritz (2015) studied the relationship between a decision maker's cognitive profile and the bullwhip effect. As such, this research is moving beyond a narrow discipline lens to offer a more complete composite of the problem and develop innovative solutions not possible from a single disciplinary view.

Methodological diversity

The ability to provide solutions to contemporary challenges, especially sustainability in supply chains, requires research methods that scale beyond the traditional areas of inquiry. As noted by Boyer and Swink (2008), "a holistic understanding of... supply chain management demands multiple approaches." Methodological diversity, rather than a single method, is needed to support interdisciplinary research (Ketter et al. 2016).

As a case in point, a funded multidisciplinary effort at the College of William & Mary to addresses "Sustainability in the Chesapeake Bay" brings together researchers in marine science, geology, economics, ecology, law, English, policy, and business to explore sustainable impacts and solutions for the nation's largest estuary. The initiative's goals state: "...impacts of climate change are beginning to be felt both locally and globally, and it is expected that future environmental change will influence terrestrial, aquatic, and atmospheric systems, their linkages, and interdependent human communities. There is tremendous need to develop capacity across science, policy, and business to conduct the research necessary to better understand these effects, develop solutions focused on sustainability and resilience, and increase/enhance communication among researchers and between researchers and the public. Given the increasing complexity and varied dimensions of environmental problems, successful cooperative learning strategies and effective multidisciplinary teamwork will be essential." (Canuel et al. (2017). Interestingly, the initiative has spawned a course "Sustainability in the Chesapeake Bay" in which Analytics and Supply Chain majors work with students in arts, media, sciences, and economics to explore connections between these seemingly disparate disciplines to address relevant issues on Sustainability in the Chesapeake Bay. The initiative and the course use diverse large datasets, data science and econometric methods, and case studies to communicate the results.

This initiative exemplifies the paradigm we are advocating. The use of a dominant method in one's field may prove too narrow or too simplistic to capture complexities of wicked problems. Rather a multimethod framework may be most supportive of interdisciplinary research. This means utilizing a variety of methods—case study, data mining and visualization, analytical, empirical, and computational methods—to address and communicate the various aspects of the problem. We suggest researchers become open to divergent methodologies and not remain dogmatic in the methods they deem acceptable.

PAPERS IN THIS STF

The papers in this Special Topic Forum address some of the dominant themes that represent the nexus of sustainable supply chains in the digital era. The first paper, titled "Using Country Risk to Inform Sustainable Supply Chain Management: A Design Science Study," looks at how country sustainability risk can inform sustainable supply chain management decisions, in particular with regard to individual suppliers. Drawing on institutional theory, the authors offer insights on the emergence of environmental, social, and governance-related country-level sustainability risk, developing a supply chain sustainability risk (SCSR) map. They offer a technological solution design going on to illustrate implications for sustainable supply chain management. This paper showcases how a technological solution design can directly inform managers about SCSR at the country level, and serve as a decision basis for the management of individual suppliers.

The second paper, titled "Logistics Innovation and Social Sustainability: How to Prevent an Artificial Divide in Human-Computer Interaction," outlines a theoretical framework describing different levels of acceptance and trust as key elements of the human–computer interaction and point to the possible danger of an artificial divide at both the individual and firm level. Looking at social aspects of sustainability with a focus on logistics workers, the authors identify human–computer interaction (HCI) as a cornerstone for the success of technical innovation in the logistics and supply chain sector. As a major part of social sustainability, the authors note that this interaction is changing as artificial intelligence applications (Internet of Things—IOT, autonomous transport, Physical Internet) are implemented, leading to larger machine autonomy. This is particularly true in logistics and supply chain management. We are witnessing the transition of humans from holding a primary executive role to a supervisory role of human operators. This leads to the fundamental question of the level of control transferred to machines, such as seen with autonomous vehicles and automatic materials handling devices. Key problems identified are a lack of human trust toward automatic decision making and an inclination to override the system. Based on four benchmark cases in the logistics industry, the authors create a classification of the roles of human employees in adopting innovations to prevent an artificial divide between humans and machines, thereby increasing social sustainability.

CLOSING THOUGHTS

Last year, the IPCC released its fifth assessment[17] of climate with a warning. It finds that "limiting global warming to 1.5°C would require 'rapid and far-reaching' transitions in land, energy, industry, buildings, transport, and cities. Global net human-caused emissions of carbon dioxide (CO2) would need to fall by about 45 percent from 2010 levels by 2030, reaching 'net zero' around 2050."

This warning is a clarion call for action for sustainable supply chains. Supply chain planners have an important role to play in greenhouse gas mitigation since sourcing, manufacture, transport, and distribution in industrial supply chains are a major part of global emissions.

Coincidently, the World Economic Forum last year released a list of global risks[18] faced by companies. The five most likely were extreme weather conditions, natural disasters, cyberattacks, data privacy, and failure of climate change mitigation—all of which make the case for firms to recast and reengineer their supply chains to be more sustainable.

What we sought to do in this commentary is to introduce some of the data-driven technologies that can enable sustainable supply chains. These technologies can help firms prototype and design sustainable products quickly and efficiently ("cradle-to-cradle" design, for example), help tailor them to customer needs (through AI), and manufacture (or customize) it close to customer demand (through 3D printing or connected robotic manufacturing). They will help manufacturing and distribution use fewer resources and be more eco-efficient. They will help procurement assure supply by directly connecting and working with the suppliers in an ethical and fair manner. These technologies will help in track and trace (Blockchains, connected devices) in the supply chain which can lead to better monitoring assets, reducing disruptions and efficient transactions. Finally, these technologies also help in maintaining the "commons"—resources (like natural wonders) that belong to all citizens. These technologies also come with their pitfalls—data privacy and security, machine bias, economic and political implications as the labor force is displaced by robots and in some cases (server grids that hold these enormous datasets, for example) at a considerable cost to the environment.

Academia also needs to raise up to this challenge. Schools (especially B-Schools) need to make sustainability an integral part of the curriculum. Students need to be trained on how to analyze big and varied datasets; use these new technologies; and be able to interpret how decisions impact the triple bottom line (not just profits).

We are optimistic that the supply chain community will raise to this challenge of "net zero" by 2050. We really do not have a choice.

[17]See https://www.ipcc.ch/2018/10/08/summary-for-policymakers-of-ipcc-special-report-on-global-warming-of-1-5c-approved-by-governments/

[18]See the World Economic forum report on global risks: http://reports.weforum.org/global-risks-2018/?doing_wp_cron=1561080974.9567980766296386718750

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