

A Smart-City Scope of Operations Management

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We are entering an era of great expectations towards our cities. The vision of “smart city” has been pursued worldwide to transform urban habitats into superior efficiency, quality, and sustainability. This phenomenon prompts us to ponder what role the scholars in operations management (OM) can assume. In this essay, we express our initial thoughts on expanding OM to the smart-city scope. We review smart-city initiatives of governments, industry, national laboratories and academia. We argue that the smart-city movement will transition from the tech-oriented stage to the decision-oriented stage. Hence, a smart city can be perceived as a system scope within which planning and operational decisions are orchestrated at the urban scale, reflective of multi-dimensional needs, and adaptive to massive data and innovation. The benefits of studying smart-city OM are manifold and significant: contributing to deeper understanding of smart cities by providing advanced analytical frameworks, pushing OM knowledge boundaries (such as data-driven decision making), and empowering the OM community to deliver much broader impacts than before. We discuss several research opportunities to embody these thoughts, in the interconnected contexts of smart buildings, smart grid, smart mobility and new retail. These opportunities arise from the increasing integration of systems and business models at the urban scale.

Key words: smart city; urban-scale integration; smart grid; shared mobility

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1. Introduction

Urbanization is one of the most transformative trends in the twenty-first century. United Nations project that around 7 billion people will live in urban areas by 2050, accounting for 70% of the world’s population. Also rising is their expectation of living standards. Currently, city inhabitants consume 75% of the world’s resources and energy, and in doing so emit 80% of greenhouse gases (Mohanty et al. 2016). Without proper measures, cities are anticipated to cause increasingly unbearable environmental and societal consequences, such as pollution, congestion, and unaffordable living. It is thus imperative for humanity to transform urban habitats toward superior efficiency, quality, and sustainability.

The boom of the “smart-city” movement in recent years reflects the above urge for a paradigm shift of cities. According to Caragliu et al. (2011), a *smart city* is an urban space of sustainable economic growth and high quality of life, enabled by human and social capital, physical and cyber communication infrastructure, with wise management of natural resources. In pursuit of such a paradigm, cities across the globe have raced to launch smart-city initiatives. Europe, India,

China, Austria and even some historically underdeveloped African countries are rolling out ambitious urban development roadmaps or national smart-city strategies (Acuto et al. 2018). In October 2016, 170 nations agreed to an UN’s New Urban Agenda to highlight the central role of urban development for ensuring a sustainable future (United Nations 2016).

Nevertheless, a smart city cannot be built in a day. Each of its components, such as buildings, mobility, energy, water, healthcare and marketplaces, needs to be innovated. Moreover, a smart city is a system of systems. It entails effective governance as well as digital infrastructure to orchestrate different components while respecting diverse human needs. As Harrison et al. (2010) state, a smart city is “connecting the physical infrastructure, the information-technology infrastructure, the social infrastructure, and the business infrastructure to leverage the collective intelligence of the city.” Hence, developing smart cities calls for synergized efforts with multi-disciplinary approaches, and has already intrigued researchers in the fields of computer science, economics, and civil engineering. However, academia is still lagging behind, according to a recent *Nature Sustainability* Expert Panel (Acuto et al. 2018): Without forging new knowledge out of

existing disciplines that are compartmentalized, we run the risk of prescribing incomplete solutions in battling complex urban challenges.

Seeing the trends, we, as operations management (OM) scholars, ponder what role we can assume in this grand smart-city movement. In particular, how to define a smart city through the lens of OM, what can we contribute to facilitating its current development and shaping its future, how to benefit our own profession, and are we prepared to do so?

Based on our own understanding and interdisciplinary experiences, we express our initial thoughts on these questions in this short essay:

The first part of this essay justifies doing smart-city OM. To demonstrate the urgency of doing smart-city research, we first briefly review smart-city initiatives by governments and industry. We identify that, despite flourishing investment propositions and maturing technologies, new wisdoms in terms of perspectives, decision-making processes and managerial insights remain to be developed to embrace urban-scale systems integration and data explosion. To familiarize readers with the current smart-city research frontier, we then review ongoing research efforts in national laboratories and in other academic disciplines. Remarkable trends include increasing visibility of urban research in prestigious scientific journals as well as the rising of urban computing. Collectively, we observe that smart-city research is in the stage of capacity building, emerging as an arena where multiple disciplines amplify their value and further evolve. We proceed to argue that it is timely and relevant to develop smart-city research from our OM community. Moving forward, the smart city development will transition from being tech-oriented to being more decision oriented to maximize citywide benefits out of technologies and resources. Through the lens of our discipline, a smart city can be perceived as a system scope within which planning and operational decisions are orchestrated at the urban scale, reflective of multi-dimensional needs, and adaptive to massive data and innovation. In light of this view, OM scholars can make important contributions by providing analytical frameworks, including system modeling, decision-making methodologies, and managerial insights, which are at the heart of smart cities. Doing so will not only push the boundaries of our expertise, but also empower our community to deliver much broader impacts than before. We also review the statement in Lee and Tang (2017) that our community has long tradition of expanding the research scope to reflect the evolution of the real-world complexity. We believe that smart-city OM naturally follows this tradition.

The second part of this essay discusses several research opportunities that concretely embody our

thoughts. Those opportunities arise in different smart-city contexts, including zero-emission buildings, smart grid, electrified and shared mobility, urban logistics, and retail. We highlight that the key opportunity for OM researchers is to develop new models, algorithms, and insights for business models and urban systems that are traditionally standalone but now increasingly intertwined at the urban scale. Ignoring this transformation would leave large portion of smart city benefits untapped, or even render a city “unsmart.” We also discuss people-centered and data-driven implications for doing smart-city OM research.

The rest of the essay unfolds these discussions. Section 2 discusses the timeliness and relevance of doing smart-city OM. Section 3 presents several research opportunities. Section 4 concludes the essay. The discussions below are not meant to be comprehensive. They can be extended in many directions. Our intention is to stimulate more thoughts in our community on expanding OM to a smart-city scope.

2. Expanding Scope to Smart City: An Urgent Agenda

In this section, we first demonstrate the *timeliness* of doing research at the smart-city scope. To this end, we briefly review smart-city initiatives by governments and industry, followed by ongoing research trends at national laboratories and in general academia. Then we express our thoughts on the particular *relevance* of OM to the smart-city scope.

2.1. Drive From Governments and Industry

Facing the socio-economical challenges that arise in urbanization, governments and industry are pursuing the vision of smart city aggressively. Several largest cities in the United States are among the pioneers of smart-city pilots on various aspects (Forbes 2014): New York City is a leader in deploying information and communication devices, such as touchscreens in phone booths and metro stations, and a system of sensors in its Hudson Yards residential development. San Francisco excels in waste recycling as well as building charging infrastructure to promote the adoption of electric vehicles. At the federal level, in late 2015, the US Administration announced the “Smart Cities” initiative to invest \$160 million to fund research and stimulate technology collaborations on tackling wide range of urban challenges. This initiative was expanded 1 year later with over \$80 million additional federal funds and over 70 participating cities and communities (The White House 2016). The targeted key areas spanned climate, transportation, public safety and municipal services. The initiative

emphasized applying state-of-art technologies such as in ubiquitous sensors, artificial intelligence and autonomous driving to improve citizen's lives. An important component of the initiative was the Smart-City Challenge. The goal was to impel municipalities to team up with pioneering businesses and civic organizations to propose innovative solutions to their diverse urban challenges. Columbus, Ohio won this challenge in 2016, with its proposal to transform its mobility landscape (Smart Columbus 2017). By promoting the adoption of electric vehicles, multimodal trip planning, parking management, and smart mobility hubs, Columbus aims to improve the connectivity and safety of its communities while reducing carbon intensity. In a similar fashion, Canada recently launched its Smart-Cities Challenge in early 2018 (Infrastructure Canada 2018). Among the entrants, Toronto already partners with Google's Sidewalk Labs to invest in Toronto's waterfront to experiment a radical mix of innovative urban elements: Flexible and modular buildings will employ new scalable prefabrication approaches to cut construction time and cost, while allowing quick and easy conversion of building uses. Pop-up retail and clinics will come and go in modular buildings, providing adaptive and agile services to neighborhoods. Autonomous vehicles and garbage robots will transport waste in underground tunnels out of sight (Sidewalk Toronto 2017).

The race to launch smart-city pilot projects is equally (or perhaps more) phenomenal and more driven by strategic plans across oceans. Among the examples in Europe, Barcelona has been at the forefront of the smart-city movement since the City Council launched its smart-city strategy in 2011. Their projects holistically embrace information, communication and green technologies to improve the smartness of the city. For example, Smart Water develops tele-control of irrigation and ornamental fountains to improve water use efficiency. Orthogonal Bus Network ensures no more than one transfer between any two locations in 95% of journeys within the city. The district of innovation, named 22@, attracts numerous companies to pilot test their smart-city products (see more introduction in Central Policy Unit 2015 and references therein). More recently, Barcelona's City Council is also promoting the transition from centralized technology push towards participatory democracy in its Digital City initiative, by empowering citizens to utilize technological innovations and massive data (Barcelona Digital City 2017).

In Asia, since the Chinese central government announced the plan to pilot smart cities in 2012, more than 500 cities, including 95% of provincial capitals, have smart-city pilots ready or under construction; China also plans to nurture 100 new smart cities by 2020 (China Daily 2018). Given the large momentum

of China's economic growth, those projects emphasize long-term top-down planning for upgrading industrial structure, building intelligent urban infrastructure while improving urban living conditions. The Chinese government also promotes the agglomeration of smart cities to facilitate sharing data and public services (e.g., healthcare and education) among neighboring cities (MOHRSS 2014). Among many other examples in Asia, Singapore tops the ranking of the Global Smart City Performance by Juniper Research (Business Insider 2018). Its famous "Smart Nation" initiative identifies transportation, home & environment, business productivity, healthcare and public sector services as key domains to innovate (Smart Nation 2017). Similar scope is also identified in Hong Kong's recent Smart City Blueprint (2017). Specific projects to roll out include: (i) integrating street light poles with free Wi-Fi access and multi-functional sensors for detecting traffic and air quality; (ii) developing Smart Community Healthcare to help the elderly live comfortably and independently using assistive technologies such as tele-consultation, remote health monitoring and even care robots; (iii) improving city-wide waste management by maximizing landfill diversion and optimizing transportation arrangement. Finally, in the Middle East, Saudi Arabia made ambitious plan of building a \$500 billion mega-city named Neom, as part of its Vision 2030, to embrace 100% clean energy, new technologies (such as autonomous driving) and more liberal social governance (Bloomberg 2017).

Meanwhile, industry is in close partnership with governments in the smart-city movements. Persistence Market Research (2017) estimates that the global expenditure on implementation of smart cities will be over \$3.48 trillion by 2026, with sectors of energy, security and building accounting for the largest shares. This huge market has attracted the information technology (IT) industry, led by Google, IBM, Cisco and AT&T, to pioneer smart-city information management systems (Financial Times 2015, Fortune 2016). For example, IBM aims to promote community services, governance and building management with its analytics and cognitive computing capabilities, partly through its Smarter Cities Challenge program (IBM 2018, 2017). In China, three major Chinese telecommunication companies and several leading IT companies (e.g., Tencent, Ant Financial) have signed smart-city construction agreements with more than 300 cities. As the nerve system of smart cities, the information management systems comprise sensors, wi-fi networks and computing units, featuring internet of things (IoT) and big data technologies.

Although investment propositions are flourishing and technologies are maturing, we observe that the smart city development is still in the early

stage. Most of the cities are in the process of idea generation or new technology adoption, based on projects that are segmented by sectors or districts. However, incrementing technological capacity is not at the heart of the smart-city transformation. What make cities truly smart are perspectives, decision-making methodologies, solution algorithms and managerial insights that embrace urban-scale system integration and data explosion. Such new wisdoms should be fundamentally transformed from traditional wisdoms derived from disconnected systems operations and insufficiently calibrated models (see more concrete discussion in section 3). As the smart city development moves forward, acquiring such new wisdoms will become essential for maximizing citywide benefits out of technologies and resources. Developing such new wisdoms calls for tremendous research efforts concerning all aspects of smart cities. Below we briefly review some research trends.

2.2. Drive From National Laboratories

The timeliness of doing smart-city research is manifested in national laboratories' research efforts. National laboratories such as those affiliated to the US Department of Energy undertake large-scale, government-funded and mission-oriented research initiatives. Those initiatives often reflect emerging societal needs. Smart-city research efforts are gaining momentum in national laboratories in recent years, mainly along two directions: (i) The first direction is to develop infrastructure of obtaining multi-dimensional data of cities. For example, Argonne National Laboratory collaborate with the University of Chicago to carry out the "Array of Things": They deploy interactive and modular sensors extensively outside buildings and along the road networks of Chicago to collect real-time data about pedestrian activities, air quality, road conditions, factory activities and so on. In doing so, along with developing computational models, they envision to help urban researchers form insights into the interdependencies of various urban factors. (ii) The second direction is to integrate models and analysis tools of different domains into comprehensive analysis platforms. For example, at the Lawrence Berkeley National Laboratory, researchers specialized in urban transportation and in electrical grid are co-developing a calibrated agent-based simulation platform to study the impact of electric vehicles on city mobility and on the electrical grid (Sheppard et al. 2017). Researchers that are traditionally specialized in building energy now bring data of city building stock, geographic information and human behavior into their building energy simulation tool

"EnergyPlus" to enable citywide energy planning (Hong et al. 2016).

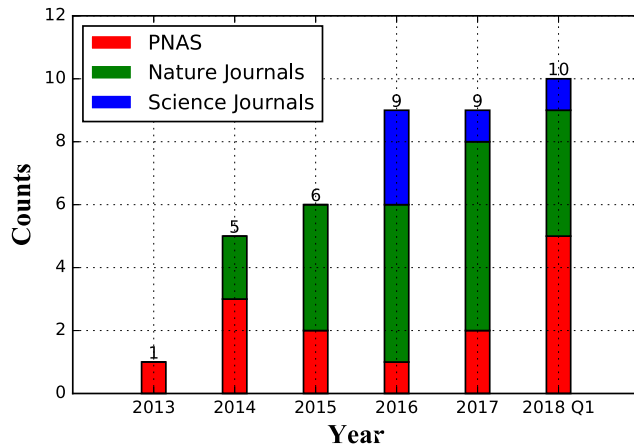
Collectively, those research efforts at national laboratories are in the stage of capacity building. They expand research to the city scope while taking into account microscopic activities. With advancements in computing capabilities, their efforts are expected to generate predictions of outcomes of different smart-city investments, and potentially discover new research questions.

2.3. Drive From Academia

Smart-city research is booming in academia. Historically, urban studies have been led by the field of civil and environment engineering as well as urban planning, naturally because of their focus on urban facilities and their expertise in modeling, simulation, and policy studies. However, smart cities involve interconnected systems, big data and diverse perspectives. Solving those problems require (and help advance) multi-disciplinary approaches. Generous research funds, such as \$35 million from the National Science Foundation in 2016 as part of the federal level smart-city initiative, also attract many science and engineering fields. Consequently, joint smart-city research institutions have been created, such as MIT Senseable City Lab, UC Berkeley's Smart Cities Research Center, and the University of Chicago's Urban Center for Computation and Data, among many others.

We observe increasing visibility of urban research in prestigious scientific journals. We examine related research articles published in three groups of journals: (i) *Proceedings of the National Academy of Sciences of United States (PNAS)*; (ii) *Nature*, *Nature Communications*, *Nature Climate Change*, *Nature Energy* and *Nature Sustainability*; and (iii) *Science* and *Science Advances*. Here we define "smart-city-related" articles as those reporting major research findings concerning urban transportation, energy, economics, living conditions, etc. Figure 1 shows an upward trend of those publications from January 2013 to March 2018. Admittedly, this trend is biased by the fact that several journals were launched after 2013 (e.g., *Science Advances* since 2015, *Nature Energy* since 2016 and *Nature Sustainability* since 2018). Nevertheless, the establishments of those journals with their coverage of smart-city research highlights the increasing smart-city research momentum in academia. Among those papers, some report cutting-edge methodologies of solving urban challenges. For example, Li et al. (2015) in *PNAS* use percolation theory to identify critical traffic bottlenecks. Some other papers identify opportunities of significantly improving urban efficiency. For example, Jain et al. (2017) in *Nature Energy* show that optimally planning and managing distributed energy

Figure 1 Numbers of Smart-City-Related Research Articles Published in PNAS, Nature Journals and Science Journals from January 2013 to March 2018 [Color figure can be viewed at wileyonlinelibrary.com]



resources reduces the levelized cost of electricity by nearly 50%. Alonso-Mora et al. (2017) in *PNAS* show that using 2000 cars (i.e., only 15% of the taxi fleet) of 10 seats for ride-sharing can efficiently satisfy 98% of the taxi trip demands in New York City.

One remarkably thriving field concerning smart city is *urban computing*, where computer science meets city-related fields such as economies, transportation, energy, sociology to address big challenges in urban spaces. Urban computing aims to tackle two layers of complexities: The bottom layer is the acquisition and management of urban data, which are usually of high dimension and volume, poorly structured, sparse and biased. The top layer applies advanced data analytics methodologies to identify and solve urban challenges. Since its inception in 2004, urban computing has fruitfully addressed a wide spectrum of problems concerning urban economy, sustainability and security. Research examples include inference of urban air quality, location selection of ambulance stations, prediction of citywide crowd flows, etc. For more details of urban computing, we refer readers to the Urban Computing Group of Microsoft Research (<https://www.microsoft.com/en-us/research/project/urban-computing/>) and their survey paper Zheng et al. (2014). Some of their research has turned into real-world implementations (e.g., air quality forecasting in more than 300 cities in China, gas consumption & pollution estimation in Guiyang, China).

The above institutional and research trends suggest that the smart-city context is emerging as an arena where multiple disciplines amplify their value and evolve. This is due to three driving forces: (i) Fundamentally, cities become increasingly central to our environment and society. (ii) The context of cities provides tradeoffs and data that are increasingly rich and

interesting. (iii) The advances in computational capabilities empower researchers to evaluate research questions at increasingly large scale. These three driving forces are all closely related to the mission and expertise of the OM profession. They prompt us to discuss the particular relevance of OM research to the smart-city development below.

2.4. Drive From within the OM Community

Having observed the increasing pursuit of smart city in society and academia, especially the rise of urban computing from computer science, we feel that it is timely and relevant to develop smart-city research from the OM community. In particular, we have the following thoughts:

What is a smart city through our lens: Current general perception of smart city needs to evolve to adapt to future smart-city development. Our survey shows that most of the existing definitions of smart city, such as those summarized in Dameri and Rosenthal-Sabroux (2014), focus on specifying what components are needed for a city to be smart. Typical choices of the components include several technologies (concerning information and communication, energy efficiency, healthcare and transportation, etc.). A few definitions mention governance enhancement, yet again driven by information and communication technologies. Those “tech-oriented” definitions reflect the current stage of smart-city development, that is, idea generation and new technology adoption. However, the next stage of the smart-city development will shift focus onto how to maximize citywide benefits by properly utilizing technologies, along with human, natural and data resources. To adapt to this stage transition, tech-oriented definitions of smart city should give way to more “decision-oriented” definitions, which are particularly relevant to OM.

Through the lens of OM, a smart city can be perceived as a system scope within which planning and operational decisions are orchestrated at the urban scale (which is beyond the traditional boundary of supply chains), reflective of multi-dimensional needs (e.g., efficiency, sustainability, social security), and adaptive to massive data and innovation. In light of this decision-oriented definition, it is imperative for our community to make contributions to the smart-city movement.

What can we contribute: Practitioners and researchers in engineering fields have largely focused on two aspects of smart cities: (i) enabling the physical and digital infrastructure; (ii) large-scale simulation and heuristics for city operations. While these efforts are essential, OM scholars can take another leading role in building deeper understanding of smart cities. Namely, the OM community can provide analytical frameworks, including system modeling,

decision-making methodologies, and managerial insights. These analytical frameworks remain underdeveloped for municipal systems and business models that are physically and digitally intertwined at the urban scale. For instance, while researchers of simulation and computer science work on predicting crowd flows in cities, analytical models and managerial guidelines are desired for interpreting and optimally managing surge flows. The OM community is expected to make such contributions, which cannot be neglected by other fields.

How to benefit our own field: Doing OM research at the smart-city scope can help push our knowledge boundaries in two ways: First, smart cities integrate systems of different structures, dynamics and stakeholders. Characterizing their coupled relationship can induce new modeling approaches; solving for optimal planning and operational schemes at the urban scale necessitates new solution algorithms. Second, smart cities feature big data. Addressing smart-city OM problems inevitably pushes the development of data-driven modeling and decision-making methodologies. These methodologies are being actively pursued by the OM community as a way of distinguishing itself from other communities that focus on data mining or econometric methodologies (Simchi-Levi 2014). In this sense, smart city is an ideal context where the OM discipline joins computer science and statistics to advance data science.

Doing smart-city research will also improve the visibility of the OM community in academia in general, given the high relevance of smart cities to a wide array of disciplines. OM papers with a smart city context will be more likely to be published in prestigious scientific journals with high impact factors, reach a broader audience, and potentially attain more recognition from outside disciplines for the entire OM profession.

Are we prepared: We are prepared to expand the research scope to smart cities. For decades, the OM discipline has contributed to the understanding of transportation, logistics, supply chains, energy systems and the sharing-economy business models, which are all building blocks of smart cities. Moreover, empirical and data-driven decision-making methodologies that our communities develop for problems in areas such as retail have also laid foundation for tackling data-intensive problems of smart cities. As Lee and Tang (2017) state, OM researchers have long tradition of expanding research scope from areas of inventory, production planning, and scheduling to healthcare management, revenue management, socially and environmentally responsible value chains, etc. Now is the time to examine numerous interesting problems arising from the scope of smart cities.

3. Smart-City OM Research Opportunities

In the remainder of this essay, we would like to discuss several concrete research opportunities of smart-city OM to further justify our thoughts above. The main idea we identify is that those opportunities arise from the increasing urban-scale integration of systems and business models. Through the discussion, we do not attempt to delimit the scope of smart-city OM. Instead, our hope is to entice contributions from the OM community to this emerging application domain to help shape its future and, in the meantime, benefit our entire profession.

3.1. Opportunity 1: Interconnecting Smart Buildings and Smart Grids

Context 1 (Zero-emission buildings): Key to an environmentally smart city is the de-carbonization of buildings. Buildings in cities such as New York City account for nearly 75% of greenhouse gas emissions (NYC Government 2018). Such enormity of emissions spurs the pursuit of emission-light buildings. For example, Vancouver, Canada launched the goal of “Zero-Emission Buildings” to require all new buildings emit no greenhouse gas by 2030 (City of Vancouver 2016). California set the “Zero Net Energy” mandate such that all new residential buildings by 2020 and all new commercial buildings by 2030 must produce as much energy (primarily through on-site renewables) as it consumes (CPUC 2017). These aggressive policy instruments will significantly boost the development of “smart buildings” (as well as “smart homes/appliances”), which are equipped with clean technologies (concerning energy efficiency and on-site energy production and storage) and energy management systems.

Now zoom out the view from the scope of individual buildings to the scope of urban districts. Consider the interconnectedness between buildings. For example, Vancouver, along with many other cities in the world, is pushing the adoption of neighborhood renewable energy systems (NRES). According to City of Vancouver (2016), an NRES is a shared infrastructure platform that provides heating/cooling/ventilation from a centralized “energy center” to multiple neighboring buildings. The energy center harnesses a variety of low-carbon renewable energy sources, such as sewer heat and waste heat recovered from building activities. NRESs are believed to be particularly suitable for dense urban areas as well as hospitals and university campuses, since the centralized systems are scalable, and can eliminate the need for boilers and other air-conditioning equipment in individual buildings.

Challenges: The smartness of individual buildings has been actively pursued by national laboratories (e.g., LBNL) and the civil engineering research community. However, insightful guidelines for implementing NRESs have yet to be provided, awaiting OM scholars to address. Planning NRESs in urban districts is reminiscent of integrated facility location and network design problems (see Mak and Shen 2016 for a multi-domain review). As is the case in those problems, NRES planners need to jointly evaluate siting, sizing and operating decisions. More specifically, pooling energy demands at NRESs can be cost-efficient, since energy demands are stochastic, time-varying and heterogeneous across buildings. Centralized NRESs also exhibit economics of scale in collecting locally available waste heat or clean wood waste. On the other hand, accommodating heterogeneous energy demand incurs additional investment in process flexibility in producing space heating, ventilation air and hot water. For industrial plants, demanded steam pressures can also vary. For these aspects, studies on uncertainties of yield, demand and costs (Kazaz and Webster 2011, Snyder and Shen 2006), supply chain management with bidirectional flows (Guide and Van Wassenhove 2006, Souza 2013) and process flexibility (Fine and Freund 1990, Simchi-Levi et al. 2018) can all be relevant. Using NRES also incurs heat/pressure loss from distribution pipelines. Considering these details may result in non-convex optimization problems and entail solution algorithm design (Xue et al. 2016). Finally, the practice of NRES may run counter to its pursuit of neutralizing emissions. According to Vancouver's NRES guidelines, new buildings that connect to an NRES will be assumed "zero emissions ready" and thus exempted from future retrofit requirements. This incentive can potentially discourage future emission-reduction investment in individual buildings. Analysis of policy incentive efficiency that appear in the sustainable OM literature (e.g., Babich et al. 2018 on incentives for solar panel investment) can shed light upon this dilemma.

Context 2 (Transactive energy among buildings): More interestingly, beyond the scope of a neighborhood, buildings will also be increasingly coupled with electrical grids at the urban scale. Electricity of cities is undertaking transformations: from a fossil-fuel dominant to a renewables-mixed portfolio of energy production, from a supply-follow-demand to a demand-responsive pattern of power consumption, and from centralized to distributed sources of electricity generation. Future urban grid will also feature advanced metering infrastructure, which enables high-precision measuring of real-

time grid conditions and making informed consumption decisions. The implication of these "smart-grid" transformations is a "transactive energy" paradigm: Instead of passively consuming power and receiving demand-response calls from utilities, buildings in a smart city will be "prosumers"—actively trading energy as well as ancillary services on a shared platform and even forming locally efficient market clearing prices.

Challenges: While demand response and electricity pricing have been extensively investigated in the fields of power systems and energy economies (e.g., Borenstein et al. 2002, Conejo et al. 2010, Li et al. 2011), most of the studies only consider a centralized energy market and a monopolistic utility. Several recent studies, such as Qin et al. (2017), initiate the design of efficient decentralized trading processes with explicit consideration of uncertainties from renewables. To further understand how to enable an energy sharing marketplace with appropriate pricing and transaction structure, it will be worthwhile to borrow from OM scholars the analysis and insights regarding two-sided peer-to-peer service platforms, for example, Benjaafar et al. (2018a) on the implications of asset ownership, Cachon et al. (2017) on the role of surge pricing and Bimpikis et al. (2016) on spatially differentiated pricing.

Compared with sharing rides or shelter, sharing building-based energy resources creates richer content to explore: (i) Multiple structures of marketplaces may be promising, such as peer-to-peer models, prosumer-to-grid models and prosumer-to-community models (Parag and Sovacool 2016). (ii) Multiple product types are involved, such as sharing surplus generation from rooftop solar panels, sharing flexible demand, sharing unused storage capacity (Kalathil et al. 2017), and even trading emissions permits if manufacturing firms are involved (Yuan et al. 2018). (iii) The valuation of those products is intricate (as discussed in Qi et al. 2017). The sharing-enabling entities (i.e., aggregators) make decisions of electricity pricing and matching not only to incentivize prosumer participation and coordination, but also to ensure grid reliability (since excessive solar power injection can destabilize the grid).

Moreover, understanding the tension between the market efficiency and carbon emission in the energy-sharing paradigm can be a research opportunity to researchers of sustainable OM. As related studies, Zhou (2018) show that using energy storage devices to shift load may increase carbon emissions if taking the power generation mix into account. Avci et al. (2015) show that the dual objectives of reducing emissions and reducing oil dependence can be misaligned in operating a battery-switching and charging station for electric vehicles.

3.2. Opportunity 2: Integrating Smart Mobility and Smart Grid

Context 3 (Electrified mobility): Future urban mobility will feature large integration of electric vehicles (EVs). Bloomberg NEF (2018) projects that worldwide sales of EVs will surge from 1.1 million in 2017 to 30 million in 2030. This boom is largely owing to two driving forces: First, technology advancements have been steadily driving down the EV production cost and extending per-charge range; the battery charging speed is also rapidly advancing. Meanwhile, governments around the world launch stringent environmental regulations to phase out fossil fuel vehicles. For example, sales of new internal-combustion cars will be banned in the United Kingdom and France by 2040, and in India by 2030 (MIT Technology Review 2017).

Accompanying the massive EV adoption is the tension between limited capacity and surging demand for battery charging. Existing literature addresses this tension from various perspectives. Some operations research and transportation studies have pursued “smart” EV mobility by proposing strategies for planning and operating battery charging and battery switching facilities (e.g., Mak et al. 2013, Schneider et al. 2017), as well as routing EVs (e.g., Desaulniers et al. 2016, Nejad et al., 2017). The vast majority of those studies assume that the electricity supply from grid is known and exogenous. On the other hand, literature in power systems have mainly focused on coordination of large-scale charging to mitigate their negative impacts on grids (e.g., Clement-Nyns et al. 2010) and in response to electricity price signals and ancillary service calls (e.g., Ma et al. 2013, Sortomme and El-Sharkawi 2012). These papers typically assume that the charging needs are exogenously given.

Challenges: From the scope of a city, however, electrical grids and mobility systems that are smart by themselves do not automatically mean a smart city; they may even lead to an “unsmart” city. Being oblivious to either the grid or the mobility side of concerns while planning the other side will incur substantial efficiency loss. For example, Zhang et al. (2017) show that locating on a transportation network a set of EV battery charging stations that only economically satisfy EV energy demands can overload the power distribution network. The price of regret will be substantial remedial investment in upgrading substation transformers and expanding distribution lines. Alizadeh et al. (2017) also show that ignoring the interconnection between the mobility and power infrastructures may result in additional operating cost or even instability. Therefore, imposing a fixed upper limit of electricity extraction at each station is not a

systemic approach; models that effectively characterize the coupling relationship of transportation flow and power flow networks are worth developing. This can be a challenging task, since electricity flows according to Kirchoff’s laws. The alternating current power flow results in network flow problem formulations that are nonlinear and non-convex. Addressing these challenges can be partly based on recent progress in convex relaxation of optimal power flow problems such as Kocuk et al. (2016). Recent advances in direct approaches to non-convex optimization (primarily motivated by machine learning problems. See Jain and Kar 2017 for a review), such as projected gradient descent and alternating minimization, may also be extended in this context of urban infrastructure optimization. Moreover, it will be even more interesting (and challenging) to also incorporate the endogeneity of EV drivers’ charge choices. Realistically, charge demands incident into each charging station depend on the proximity of the entire charging infrastructure and the waiting time at the station. Along this direction, recent research projects such as Sheppard et al. (2017) integrate discrete choice models into microscopic transportation simulation to capture EV drivers’ charging behavior. Finally, spatially and temporally differentiated pricing of charge services may also help alleviate the stress on the grid (Flath et al. 2014).

Context 4 (Grid support from shared autonomous EVs): (i) Along with electrification, urban mobility is also shifting toward the paradigm of autonomous driving and shared usage. The revolutionizing technology of autonomous driving enables automatic navigation without human inputs. It is expected to increase safety and reduce vehicle cost, among other benefits. Meanwhile, shared mobility has already gained strong momentum in reality, with booming business models of vehicle sharing (e.g., Zipcar, Car2Go) and ride sharing (e.g., Uber, Didi). Combining these transformations gives rise to an intriguing smart-mobility future where shared autonomous electric vehicles (SAEV) prevail in cities. As Greenblatt and Saxena (2015) point out, autonomous and shared usage will significantly enhance the vehicle utilization rate and allow vehicles to be more compact, which naturally embraces EVs.

(ii) On the grid side, as aforementioned in Context 2, distributed renewable (e.g., rooftop PV) generation will penetrate future urban microgrids. These electricity injections are intermittent and non-dispatchable, posing threat to grid reliability. Moreover, as the notorious “duck curve” in California ISO (2016) illustrates, when PV power generation capacity (both in cities and on the transmission side) expands, the ramping pressure mounts on other sources of

electricity generation to balance the supply and demand. That is, dispatchable generation units have to quickly ramp down their power outputs when the sun rises, and ramp up when the sun sets, resulting in huge operating costs and low capacity utilization. Mitigating this issue calls for large storage capacity in the grid. For example, California mandates that its energy storage capacity reach 1.3 GW by 2020 (The New York Times 2013).

The above trends collectively imply that EVs are not mere liability to urban distribution grids. Instead, EVs will be a valuable asset as *mobile* energy storage resources to support grids. While some OM and power systems literature have investigated the vehicle-to-grid (V2G) benefits (such as Broneske and Wozabal 2017), discussion on the mobility of those energy storage assets has been rare (recently, Kahlen et al. 2018 consider V2G with endogenous EV spatial dispatch only for satisfying trip demands). Ideally, EVs can be directed to charge batteries where excess PV generation that congests the microgrid needs to be locally consumed. EVs can also discharge their batteries upon grid contingencies, or where supplying electricity entails running inefficient or carbon-intensive generation units, or where voltage support is locally needed. These potential values are particularly relevant to SAEVs, which can be operated in a centralized and scalable fashion.

Challenges: However, at the urban scale, operating SAEV fleets to jointly satisfy travel demands and support grids will be a grand challenge, due to three layers of complexity: (i) To maintain a transit service level throughout the city, the SAEV service operator needs to reposition its vehicles in real time in the presence of asymmetric travel demands. Dynamic vehicle repositioning with stochastic travel demand has received attention in recent literature. For example, Benjaafar et al. (2018b) and He et al. (2018) propose different stochastic dynamic repositioning models. (ii) For EVs, battery charging operations couple repositioning operations. The fleet operator needs to ensure that the energy level of each EV is sufficient for its assigned trip, and frequently direct its fleet to charging facilities to maintain energy balance. Boyaci et al. (2015) propose a planning model for station-based EV sharing, with joint decisions of station location, fleet size and repositioning operations. He et al. (2017) focus on free-floating EV sharing and assume a fixed portion of fleet flows for battery charging when solving for the optimal service zone planning. However, detailed battery charging operations are absent from those papers. Since shared and electrified mobility is still in its early stage, infrastructure planning for battery charging is vital. Planners need to take into account the coupled charging and repositioning

operations when evaluating the decisions of siting and sizing charging facilities throughout the city.

(iii) Finally, using SAEV to support grid invites more unanswered research questions. For example, how to quantify the value of the mobility of those storage devices? Can cross-borough charge and discharge operations of SAEVs help mitigate solar energy curtailment due to grid congestion, and/or help enhance the self-sufficiency of local microgrids? What should be a proper fleet size and how to provide adequate “spinning” reserve to the grid in case of random drop in solar power outputs? Given the literature cited above, we believe that the current know-how that OM scholars have obtained from inventory management, resource allocation, facility location and energy systems management can be further extended to answer those questions in the smart-city context.

3.3. Opportunity 3: Emerging Service Integrations

Smart cities blur the boundaries between service industries that are traditionally separate from each other. The sharing economy onward not only implies sharing capacity for one particular service, but also implies integrating different services to further enhance resource utilization efficiency. Emerging service integration business models create rich contexts, for which traditional models and insights may fail to characterize. Below we discuss two cases.

Context 5 (Integration of people transit and package distribution): Urban shared mobility has been primarily sourced for ride sharing and vehicle sharing—both for people transit. However, recent years have witnessed the growth of crowdsourcing shared mobility for package delivery. For example, Uber Rush offers on-demand point-to-point express delivery. Uber Eats focuses on on-demand home delivery of meals from restaurants. Amazon Flex crowdsources Uber drivers for Prime Now, a 2-hour instant home delivery service guarantee.

Challenges: As the integration of package delivery services scales up, it becomes worthwhile to understand the management strategy and implications of such hybrid business model. A few studies have partially addressed this research need, yet under restrictive settings. For example, Li et al. (2014) formulate vehicle routing problems and solution algorithms to study the “share-a-ride” problem in which taxis are allowed to pick up and drop off parcels along passenger transit trips. Qi et al. (2018) evaluate the cost effectiveness and environmental impact of crowdsourcing on-demand shared mobility for last-mile delivery, based on continuous approximation models. The following questions remain to be explored: Should a delivery service provider reserve shared mobility in advance, or seek an Uber driver on demand? What is the impact of integrating package delivery services on

the pricing decisions of two-sided ride-share service platforms? What is the impact on the upstream bulk trucking system? What will be the optimal pool size of shared mobility to accommodate both services? Key to answering these questions is to characterize the dynamics of moving passengers and moving packages. These two services differ from each other in vehicle routes, responsiveness and scalability. The drivers' payment mechanism may also need redesign. For example, combinatorial auctions (which Caplice 2007, de Vries and Vohra 2003 survey) have been common in truckload transportation to clear bundles of items. Whether such mechanisms will be effective for clearing coupled transit and delivery service markets with shared mobility remains largely unclear.

Context 6 (Integration of mobility and retail): In a smart city, retail channels can further diversify beyond the traditional online and offline boundaries. In particular, shopping can be mobile. Several fast scaling startups, such as Cargo in the United States and Mobile Go in China, are vending products inside cars to passengers on their ridesharing trips (Cohen et al. 2018). Such business model is expected to significantly increase the product sales rate. Naturally, products receive more attention from passengers seated in a limited space for an extended period than from customers browsing numerous products online or in a brick-or-mortar store. Passengers can enjoy higher utility from the ridesharing service if the products cater to their needs (e.g., coffee for morning trips). Drivers can also earn additional commission fees from the sales of products. Such business model is aligned with the "new retail" vision from the retail industry, which also stresses the integration of online, offline, logistics and data across value chains (Forbes 2017).

Challenges: Managing mobile retail creates new research challenges. (i) First, the product assortment decisions are vital, since the shelf size in a car is constrained. Ideally, product assortment and pricing decisions should be frequently updated. This is because customers' product preferences may vary depending on when and where the car is running. For example, passengers picked up from high-income districts may have different product valuations than passengers from low-income neighborhoods; omelettes may sell more in the morning than in the evening. There have been many studies in the revenue management literature on pricing, assortment, and customer segmentation. Among them, Kök et al. (2008) provide a comprehensive review of assortment planning. Rusmevichientong et al. (2014) formulate and solve assortment problems with multiple customer segments. Chen et al. (2015) develop a statistical learning approach for customized pricing and assortment optimization. Recently, Bernstein et al. (2017)

develop a multi-armed bandit type of dynamic assortment approach for online retail, considering both dynamic customer segmentation and dynamic assortment decisions. For the mobile retail business model, the complexity in addition to those identified in literature is to take into account customer preferences that are spatially and temporally varying.

(ii) Second, the inventory replenishment policy for mobile retail should be different from that for static stores. Currently, Cargo sends replenishments to drivers' homes when supply is running low. However, taking advantage of the mobility of this business model, the retailer may save logistics cost by keeping inventory of products at selected locations across the city for drivers to load. The optimal strategy of inventory placement and replenishment for such mobile retail business model remains to uncover. Given the existing literature addressing the delivery implications for online retailing (e.g., Belavina et al. 2017 on per-order and subscription-based online grocery shopping) as well as the mature literature on location-routing-inventory problems (see Prodhon and Prins 2014 for a review), OM scholars are well positioned to reveal insights for retail business models that more deeply integrate smart mobility. Recently, Fisher et al. (2018) demonstrate the operational benefits due to increasing retail mobility in a Buy-Online-Pick-Up-In-Store setting, in which customers pick up groceries from trucks that have flexible operating locations and hours. In the case study, they estimate that optimizing truck location configuration and schedule increases revenue by at least 42%.

3.4. Opportunity 4: People Centered and Data-Driven Research

Opportunities of doing smart-city OM not only arise from the above discussed systems interconnectedness, but also arise from mixed perspectives. Ultimately, smart cities are built by the people and for the people (rather than merely for profits). Regarding "by the people," stakeholders in a smart city are more heterogeneous than in a supply chain, differing in their objectives, preferences and capacities. Models that do not capture such complexity may result in wrong or even inapplicable insights. For example, integrating smart mobility and smart grid needs to recognize the fact that grid operators are much more risk-averse than mobility service providers. For the former, EV supported grid must be robust against severe grid contingencies, whereas the latter mainly seeks profitability subject to mild transit service level requirements. As another example, Liu et al. (2018) find that it is not optimal to assign TSP routes to drivers when they deliver online lunch orders. Drivers have different levels of local knowledge of different neighborhoods, which affect their delivery speed. It is

thus better off learning their individual differences from historical data when assigning delivery trips. Regarding “for the people,” smart-city research should address various human needs, including safety, sustainability, service agility, reliability, resilience and privacy. The aforementioned contexts reflect some of these perspectives. As argued in Rafique et al. (2017) on designing an integrated energy supply chain, equity issues should also be considered for OM problems of large scope. Other relevant contexts include the emergence of Blockchain, Internet of Things (IoT) and Big Data. These technologies have potential for profoundly reshaping service operations and supply chain management from those people-centered perspectives. A particularly intriguing prospect is *mass customization*, that is, integrated urban systems aided by tremendous amount of data of individual citizens enable highly personalized services based on their unique characteristics (see Feng and Shanthikumar 2017 for this implication in demand learning and planning, and manufacturing).

Last but not the least, doing smart-city research can take advantage from the increasing abundance of real-world data. Part of this abundance is owing to the growing willingness of public and private sectors to open up detailed data to the public. For example, City of Chicago funds an open data portal, which keeps updating a myriad of data sets about Chicago’s urban activities such as bike-sharing trips, food inspections and crime reports. As examples of datasets or data analytics for urban mobility, Taxi & Limousine Commission, New York City (2017) publicizes NYC taxi trip records; Yin et al. (2017) use cellular data to model activity-based travel demand; and Kabra et al. (2017) and Henderson et al. (2016) study traces of bike-sharing activities in Paris and NYC, respectively. Data sets of building energy consumption include Pecan Street (2017) for households in Texas, and EERE (2017) for a myriad of building types in NYC. Data in the retail sector are more extensive, concerning product assortment (Bernstein et al. 2017), promotion vehicles (Baardman et al. 2018) and social media information (Cui et al. 2017), etc. Cainiao releases comprehensive records of online retail transactions and logistics to the OM community to stimulate the research of retail analytics (MSOM 2018). In fact, essential to a smart city is a layer of digital infrastructure, which not only creates and processes massive amounts of data of individual components of a city, but also enables connectivity across those components. For OM scholars, the challenges and opportunities are to utilize cross-sector data and derive models and managerial insights at the scope of a smart city.

4. Conclusions

In this essay, we briefly discussed some thoughts on expanding OM research to the smart-city scope. We reviewed smart-city initiatives by governments and industry, followed by research activities at national laboratories and in academia in general. We observed that the smart-city development is still in the stage of idea generation and new technology adoption. Moving forward to the next stage where smart-city development shifts from being tech-oriented toward being more decision-oriented, we argued that it is timely and relevant to seize the opportunity of doing OM research at the urban scale. The key contribution made by the OM community will be providing advanced analytical frameworks for deeper understanding and improved operations of smart cities. Doing so will not only push our knowledge boundaries (such as data-driven decision making), but also enable our communities to deliver much broader impacts than before.

We discussed several research opportunities concerning smart buildings, smart grid, smart mobility, and new retail, which are interconnected at the urban scale. The idea we strived to convey is that OM questions arising from those contexts are rich, exciting and impactful. Meanwhile, there are many other topics that we omitted, such as energy-water nexus, healthcare delivery, urban emergency management, parking management, urban agriculture, among many others. Those research frontiers have been separately explored by our profession in the past; however, in this new era with emerging IoT and Big Data technologies, it is imperative to examine those systems and business models at the urban scale.

While we emphasized the integrative perception of urban space, we would also like to emphasize that such integration is not merely to piece together existing models in a mechanical way. As discussed in the case of smart grid and smart mobility, we need to be mindful about model complexities and competing objectives. Decision-making frameworks need to be transformed to be more data-driven to accommodate big data. To ensure the relevance of their findings, OM scholars should frequently talk to practitioners, policy-makers and scientists of other disciplines or at national laboratories. With these efforts, we believe that the OM community will further thrive and play an indispensable role in shaping a smart-city future.

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