Chapter 31
Defining Computational Urban Science

Xinyue Ye, Ling Wu, Michael Lemke, Pamela Valera, and Joachim Sackey

Abstract Uncovering the multi-dimensional interplay between computation and urban life's spatial-social aspects has both theoretical and practical implications for urban planning and public health science. Many analytical methods have been implemented and applied to deal with high-dimensional, heterogeneous, and unstructured location-based social data drawn from urban locales. Computational urban science has four interdependent layers: human dynamics-centered, platform-based, action-oriented, and convergence-driven. As a research paradigm based on computational thinking and spatiotemporal synthesis, computational urban science can provide a needed framework for addressing many pressing urban sustainability challenges from a systematic perspective.

Keywords Computational urban science · Human dynamics · Computational science · Urban science · Community engagement · Convergence

31.1 Introduction

World-wide, unprecedented urban growth has generated fascinating issues for interdisciplinary scholarly research. Urban communities in the twenty-first century have increasingly transitioned into complex systems and systems-of-systems, consisting of many dynamically interdependent human, environmental, and technical systems (Bibri, 2021). Simultaneously, advances in Information Communication Technology have been accompanied by social innovations, which continues to drive the techno-centric versus human-centric debates (Costales, 2022). In this context, new urban data involves the life qualities and connections that characterize individuals and/or

X. Ye (✉) · L. Wu
Texas A&M University, College Station, Texas 77840, USA
e-mail: xinyue.ye@tamu.edu

M. Lemke
University of Houston-Downtown, Houston, Texas 77002, USA

P. Valera · J. Sackey
Rutgers, The State University of New Jersey, New Brunswick, USA

B. Li et al. (eds.), *New Thinking in GIScience*,
https://doi.org/10.1007/978-981-19-3816-0_31

communities in urban areas. Rapid growth in urbanization and intensive urban–rural interaction enables massive flows of virtual and physical elements, including people. At the same time, an increasing number of extreme weather-driven urban hazards are a significant source of biodiversity loss, social disruption, and economic disparity, threatening progress towards the United Nations' 17 Sustainable Development Goals (Ye et al., 2021a, 2021b). In response, the United States and China have recalled the Paris Agreement's aim to address the challenges of the global climate crisis, pursuing efforts to limit the increase of global average temperature to below 1.5 °C (U.S. Department of State, 2021).

The U.S. National Science Foundation summarized the following key research questions to address continued and emerging challenges relevant to urban sustainability (NSF, 2020): (1) How can science improve forecasts and make predictions about the future states of rural, suburban, and urban systems? (2) What theories explain the structure and function of communities in the twenty-first century and what are the critical drivers to social change? (3) What aspects and intersections of social, built, and natural systems influence the resilience and sustainability of communities and the well-being of the people living in them? (4) How can successful innovations in one community be transferred to other communities? (5) How can integrative research along with community engagement improve the quality of life in those communities? To address these research questions and enable more resilient responses to persistent and emerging challenges associated with urban growth (Ye et al., 2021a, 2021b), a framework of computational urban science (CUS) is needed in the context of complexity systems. The advantages of incorporating elements of complex systems (e.g., dynamic complexity, interactions, etc.) shed light on the aforementioned questions raised. Incorporating computational science into urban science and vice versa has led to the increasing popularity of CUS (defined as urban computing in engineering schools or public informatics in public policy schools). At the same time, CUS should not be limited to either urban science or computational science; instead, it is a new research paradigm of studying urban phenomena based on computational thinking and spatiotemporal synthesis. CUS is composed of four layers: (1) Human dynamics-centered, (2) Platform-based, (3) Action-oriented, and (4) Convergence-driven. Together, these four layers that constitute CUS can contribute to urban sustainability in the twenty-first century through the integration of multidisciplinary and transdisciplinary theory, methodology, analysis, action planning, and community engagement.

31.2 Human Dynamics-Centered

Human dynamics-centered CUS aims to put humans at the center of technology driven advances to optimize the human–environment interaction in the built environment. Understanding human dynamics would facilitate the development of human-centered CUS towards a trans-disciplinary field of research and practice drawing on three elements: people, place, and space. To appreciate cities, we must view them as systems of networks and flows to better understand an individual by examining his/her social ties and interactions (Batty, 2013). The growing volume and diversity of human data in the urban communities further justify the need for human dynamics-centered CUS. The critical importance of centering human dynamics within CUS is grounded in historical and contemporary insights. Hägerstrand (1953) argued that human communication is mainly constrained by geographical social networks, indicating that social actions are spatially organized. Hence, Tuan (1977) pointed out that a place is a social construction of physical space, with special meaning for each individual across time. Nowadays, data logs from individual activities and interactions are typically collected at a fine-scale spatial and temporal level, thus bringing human-centered analytics to the frontier of urban science. Barabasi (2005) highlighted the role of human dynamics from a complex network perspective in revealing the mechanisms underlying many complex social, technological, and economic phenomena. Shaw et al. (2016) emphasized the geographical view of human dynamics research in the context of the emerging mobile and big data era.

Bringing a humanistic approach to the centre of urban computing helps us revisit the traditional urban theories and allows us to observe the role of computation shifting from lab-based academic use by research groups to urban daily use for individuals. User-generated data is by nature multi-scale and can be harnessed to gain insights into the urban activity structures (Huang et al., 2021; Steiger et al., 2016). With growing investments from government and business, the increasing affordability of technology and infrastructure can enable a revolution in urban management because decision-makers can more rapidly understand citizens' feedback and incorporate this information into policymaking. In this way, research insights derived from CUS can change our lives and neighbourhoods more instantly. Human dynamics-centered CUS can also re-orient urban management from the centralized and top-down that currently represents the status quo to a decentralized and bottom-up perspective, providing a more democratized decision- and policy-making environment in urban areas (Batty, 2013).

31.3 Platform-Based

A platform-based system is a process of developing, implementing, and refining a complex systems-based procedures that can serve as a critical enabler for the empirical study of space–time dynamics within urban environments. Platform-based CUS is expected to derive knowledge from heterogeneous streams of big urban data. Furthermore, a platform-based CUS has the added value of being a signaling term to attract more attention from industry. Computation is the essential methodological platform for urban data fusion, data mining, and simulation (Kontokosta, 2021). With fast-evolving disruptive digital technologies, such platforms will trigger new modes of analytics that could tackle the fine-scale data-rich urban environment and thus simultaneously advance both computational science and urban and social science. Gelernter (1993) predicted that software can go beyond codes and tools and towards "crystal balls" where we can observe and deeply understand the urban world. In addition, such "crystal balls" can facilitate computer-aided urban scenario experiments by leveraging a virtual urban environment workbench integrating "multi-dimensional visualization, dynamic phenomenon simulation, and public participation" (Lin et al., 2013; Wan et al., 2021).

Advances in artificial intelligence (AI) present additional opportunities to help address some of the most pressing and enduring urban challenges. Platform-based CUS can serve as common ground for the long-term collaborations between AI researchers and application-domain urban experts. For instance, cutting-edge sensing technologies are increasingly adept at recording urban mobility patterns in massive trajectory datasets, such as the movements among humans, taxis, buses, fleets, and cars. Visualizing and analysing such big dynamic data plays a critical role in knowledge discovery with an appropriate platform for trajectory data management and interactive visualizations facilitating user engagement (Ye et al., 2021a, 2021b). A large number of users, including students, teachers, researchers in various urban domains, and data analysts and software developers from industrial sectors need more open-source platforms to utilize big urban datasets better and transform these data into actionable knowledge. The revolution of computation as a platform for urban science has further blurred the boundaries of sub-disciplines in urban research. At the same time, the increasing affordability of computing and the flatter learning curve has removed long-standing barriers that had previously hindered the proliferation of computing platforms across disciplines.

One of the novelties involved with CUS is the creation of digital twins of existing cities for policymaking and design, which can weave the four layers mentioned above. A digital twin is a digital representation of a physical object or system, linked to real-time data inputs (Li et al., 2021). Such technologies have expanded to include large items such as buildings, factories, and cities. Digital twin technology has moved beyond manufacturing and into the merging worlds of AI and big data analytics. Through such an approach, computer programs take real-world data about a physical object or system as inputs and produce, as outputs, predications, or simulations of how that physical object or system will be affected by other inputs. The participants will also be afforded the ability to conduct experimental research in built environments through the use of mobile devices. By linking urban sensors with the developed digital twin with advanced virtual and augmented reality technologies, we can provide contextualized, real-time in-situ modelling of cities, which can be used to dynamically analyse real-time built environments and test scenarios for sustainable urban growth.

Through software and hardware integration, digital twin can be used for action to address the built environment challenges. It will enable ubiquitous networked immersion and virtual human teleportation to any location and scale of the built environment to assist humanity in solving current societal challenges and design needs. For example, the capabilities to accurately visualize and dynamically update the conditions of underserved and marginalized communities will afford such communities with the data to create real change in their neighbourhoods and solve existing and future racial inequity issues. Simultaneously, the ability to model climate change-based scenarios and test their impacts on the built environment offer unprecedented capabilities for altering the projected effects of issues such as sea-level rise. Such capabilities have tremendous possibilities for flood preparedness and recovery in coastal communities, which can be applied globally. It would enable a scalable simulation and interactive visualization platform that reveals the interactions and dynamics of urban flows, entities, and social phenomena from site/community to the regional/national scale. For example, a user can trigger a virtual fire, building collapse, or natural disaster (e.g., flood event, chemical plant explosion, etc.), and/or observe the predicted behaviour of pedestrians and other inhabitants. We can simulate how communities will be transformed by moving to autonomous vehicles. These platforms would also allow the understanding of existing urban infrastructure conditions and how to increase its efficacy.

31.4 Action-Oriented

CUS can inform high-impact, sustainable, and citizen-driven action planning, interrelationships, and policymaking, thereby empowering the decision-making of individuals, communities, and other key stakeholders. There are growing interests in utilizing big urban data for a broader audience in government agencies, practitioners, and citizens. Urban data contains abundant knowledge about a given city and its citizens. The extracted information through CUS can be utilized in many important and practical applications to optimize urban planning and improve built environments in urban settings. Both the Columbia Climate School (established in 2020) and the Climate and Sustainability School at Stanford University (established in 2022) have identified transdisciplinary initiatives to develop actionable, evidence-based, and realistic pathways for impacting communities, which is expected to be highly relevant to urban science. For example, the Envisioning the Neo-traditional Development by Embracing the Autonomous Vehicles Realm Institute (ENDEAVR Institute) at Texas A&M University aims to translate emerging urban computing technologies into action-oriented solutions for small communities (ENDEAVR, 2022). ENDEAVR Institute also serves as an interdisciplinary project-based learning platform that connects science, technology, engineering, art, and mathematics disciplines with industries and communities.

The field of public health is focused on improving health and addressing health inequities of populations, communities, and individuals through prevention, health promotion and implementing interventions. With recent advances in information technology, big data, and communication technology, we can collect, analyse, and store large volumes of real-time data at the population level. The field of information technology, urban/social science, and public health are converging into the study of complex environments calling for a comprehensive review of how to achieve better outcomes and interventions to address those contemporary issues effectively. An example is how during the COVID-19 pandemic, some testing and vaccination centers were overwhelmed whilst others were not. A better understanding and implementation of CUS could enable health authorities to plan better. Another example is using geolocation data to estimate physical activity and how people move to access food. This information could be used to help authorities improve the built environment and decide where to allocate resources. The Healthy People 2030 also has several action objectives that can benefit from better integration with CUS, such as "reduce the number of days people are exposed to unhealthy air", "increase trips to work made by mass transit", and "increase the proportion of adults who walk or bike to get places".

31.5 Convergence-Driven

Advancements in location-aware technology, information and communication technology, and mobile technology during the past two decades have transformed the focus and need of built environment research. It moves from mostly indoor-based, community-level, or metropolitan-scaled static assessments to spatial, temporal, and dynamic relationships that integrate human behaviours across multiple environments and scales (mixed environmental models now including natural, built, and virtual elements). Simultaneously, projections show that, globally, more people will live in areas designated as vulnerable or high-risk relative to contemporary and future urban issues (e.g., sea level rise, depopulation, natural disasters, etc..), which suggests that urban communities will experience increases in multi-hazard risks. Disasters cause significant sources of property loss, social disruption, and inequality. Communities can reduce vulnerability while increasing social and physical resilience through research-driven and evidence-based planning, design, and policy development. However, silos within the design, social, and engineering sciences, and gaps between research and practice have made sustainable and equitable development difficult.

Given the interconnected systems and systems-of-systems that are inextricably tied to human dynamics and are ubiquitous within urban environments, complementary approaches that can embody diverse theories, methodologies, and data types are necessary. Thus, themes of CUS are increasingly towards the convergence and synthesis of theories and methods across multiple disciplines, as well as big and open data, computing technology, and interactive and collaborative environments. Goodchild (2020) pointed out any single discipline cannot solve pressing social and environmental challenges, and hence integration across conceptualizations, analytical methods, and software environments is necessary. From the convergent perspective, CUS is a human-centric synthesis that is responsive to the rapidly changing data and computing environment and reflective of the multi-faceted nature of social complexity. To extract profound insights from the massive amount of urban data, users must conduct iterative and evolving information foraging and sense-making and guide the process using their domain knowledge. Hence, visualization and iterative visual exploration are important in this process that relies on the deep integration of computational science and urban science. Due to the lack of synthesis, despite myriad visualization techniques and systems developed from urban data, there remains a gap between the demand of urban researchers and the availability of free-accessor open-source software. Such tools should include interactive visualizations and provide data curation, management, and logistic functions.

31.6 Promising Outlook and Next Steps

We live in the Urban Millennium. With over three million people estimated to be moving into areas each week (Perry et al., 2021), the world's population is expected to become increasingly concentrated in urban areas, which are projected to grow from 55% to 68% of the world's population over the next 30 years (WHO, 2022). As these demographics manifest worldwide, endemic problems associated with increases in urbanization can be expected to worsen. For example, nearly half of urban growth occurs in informal settlements, which are noted for their lack of clean water and proper sanitation and are considered especially vulnerable to adverse health and safety outcomes (Vojnovic et al., 2019; WHO, 2022). Further, many of those individuals locating to urban areas have been forcibly displaced, often due to man-made forces such as climate change (Perry et al., 2021). Additionally, the growth of urban areas has gone hand-in-hand with social inequality (Loukaitou-Sideris, 2020). As a result, urbanization—and in particular, unplanned and rapid urbanization—is connected with a majority of the leading causes of death (WHO, 2022).

Meeting persistent and emerging challenges related to twenty-first century urbanization will require approaches that can meaningfully embody those complex systems and systems-of-systems that characterize urban environments. Accordingly, there is a need to create a paradigm shift to develop a systematic and theoretical framework to proliferate CUS. The CUS framework presented in this chapter can propel a paradigm shift in the state of urban science through its integration of multidisciplinary and transdisciplinary theory, methodology, analysis, action planning, and community engagement. Along these lines, the four layers that constitute the CUS framework delineated herein can contribute to urban sustainability in the twenty-first century. In particular, with its emphasis on community engagement, this CUS framework can also address longstanding issues in urban research and design, most notably historical failures of these fields to be fully participatory and inclusive and to account for justice (Loukaitou-Sideris, 2020). By collaborating with underrepresented and diverse communities and by increasing communication with these communities, the field of CUS can enable urban design that can reduce biases and create a shared language and set of norms to bring a greater understanding of underlying complex systems and systems-of-systems. As a result, CUS can provide a means for enabling authentic bottom-up input from marginalized urban communities that can enable sustainable, equitable, and just urban development moving forward.

References

Batty, M. (2013). *The new science of cities*. MIT press.
Batty, M. (2020). *Foreword I: Charting computational social science from a spatial perspective*. In *Spatial Synthesis* (pp. 3–5). Springer, Cham.
Barabasi, A. L. (2005). The origin of bursts and heavy tails in human dynamics. *Nature, 435*(7039), 207–211.
Bibri, S. E. (2021). The core academic and scientific disciplines underlying data-driven smart sustainable urbanism: An interdisciplinary and transdisciplinary framework. *Computational Urban Science, 1*(1), 1–32.
Costales, E. (2022). Identifying sources of innovation: Building a conceptual framework of the Smart City through a social innovation perspective. *Cities, 120*, 103459.
ENDEAVR. (2022). *Envisioning the neo-traditional development by embracing the autonomous vehicles realm*. http://endeavr.city/about-us/team-leaders
Gelernter, D. (1993). *Mirror worlds: Or the day software puts the universe in a shoebox... How it will happen and what it will mean*. Oxford University Press.
Goodchild, M. F. (2020). *Convergence and Synthesis*. In *Spatial Synthesis*. Springer.
Hägerstrand, T. (1953). *Innovationsförloppet ur korologisk synpunkt* (Vol. 25). Gleerupska Univ.-Bokhandeln.
Huang, X., Li, Z., Jiang, Y., Ye, X., Deng, C., Zhang, J., & Li, X. (2021). The characteristics of multi-source mobility datasets and how they reveal the luxury nature of social distancing in the US during the COVID-19 pandemic. *International Journal of Digital Earth, 14*(4), 424–442.
Kontokosta, C. E. (2021). Urban informatics in the science and practice of planning. *Journal of Planning Education and Research, 41*(4), 382–395.
Li, D., Yu, W., & Shao, Z. (2021). Smart city based on digital twins. *Computational Urban Science, 1*(1), 1–11.
Lin, H., Chen, M., Lu, G., Zhu, Q., Gong, J., You, X., Wen, Y., Xu, B., & Hu, M. (2013). Virtual geographic environments (VGEs): a new generation of geographic analysis tool. *Earth-Science Reviews, 126*, 74–84.
Loukaitou-Sideris, A. (2020). Responsibilities and challenges of urban design in the 21st century. *Journal of Urban Design, 25*(1), 22–24.
NSF. (2020). *Urban systems and communities in the 21st century*. https://www.nsf.gov/ere/ereweb/c21c/index.jsp. Released on September 16, 2020.
Perry, G., Upchurch, C., & Kline, L. (2021). *Displacement, migration, and urbanization in the 21st century*. Wilson Center.
Shaw, S., Tsou, M., & Ye, X. (2016). Human dynamics in the mobile and big data era. *International Journal of Geographical Information Science, 30*(9), 1687–1693.
Steiger, E., Resch, B., & Zipf, A. (2016). Exploration of spatiotemporal and semantic clusters of Twitter data using unsupervised neural networks. *International Journal of Geographical Information Science, 30*(9), 1694–1716. https://doi.org/10.1080/13658816.2015.1099658
Tuan, Y. F. (1977). *Space and place: The perspective of experience*. University of Minnesota Press.
U.S. Department of State. (2021). *U.S.-China joint statement addressing the climate crisis*. https://www.state.gov/u-s-china-joint-statement-addressing-the-climate-crisis/
Vojnovic, I., Pearson, A. L., Asiki, G., DeVerteuil, G., & Allen, A. (2019). Global urban health: Inequalities, vulnerabilities, and challenges in the 21st century. In I. Vojnovic, A. L. Pearson, G. Asiki, G. DeVerteuil, & A. Allen (Eds.), *Handbook of global urban health* (pp. 3–32). Routledge.
Wan, G., Lin, H., Zhu, Q., & Liu, Y. (2021). Virtual geographical environment. In *Advances in cartography and geographic information engineering* (pp. 443–477). Springer.
World Health Organization. (2022). *Urban health*. https://www.who.int/health-topics/urban-health#tab=tab_1.
Ye, X., Du, J., Gong, X., Zhao, Y., Shamal, A. D., & Kamw, F. (2021a). SparseTrajAnalytics: An interactive visual analytics system for sparse trajectory data. *Journal of Geovisualization and Spatial Analysis, 5*(1), 1–11.
Ye, X., Wang, S., Lu, Z., Song, Y., & Yu, S. (2021b). Towards an AI-driven framework for multi-scale urban flood resilience planning and design. *Computational Urban Science*, *1*(11). https://doi.org/10.1007/s43762-021-00011-0