5

Defining smart cities

High and low frequency cities, big data and urban theory

Michael Batty

Introduction

Smart cities define the latest stage in the digital revolution which began with the invention of computers in the middle of the last century. Successive waves of ever smaller and more powerful computers have marked this evolution with computers and their communications first spreading out from their origins in scientific laboratories to business transactions processing in dedicated computer centres. As computers were scaled down from mainframes to minis in the 1960s and 1970s and with the advent of the microprocessor in 1971, they became personal and individualistic in the 1980s, being used as the primary devices to connect to the growing internet in the 1990s. By the millennium, mobile phones were becoming widespread, morphing into hand-held devices such as smart phones and these have predominated during the last decade. Currently (mid-2019), more than 35% of the world's population of 7.5 million persons have access to a smart phone and to all intents and purposes, by the year 2030, at least 75% will be able to connect with one another in this way.

This evolution has been governed by Moore's law, the regularity observed in the miniaturisation of electronic circuitry that began with the invention of the transistor in 1948 at Bell Labs. It was first articulated by Gordon Moore (1965), one of the pioneers of the integrated circuit in one of the first and still the world's most powerful semiconductor company, Intel. Moore observed that computer processing power was doubling every 18 months, increasing in speed in the same way, reducing in cost by one half and scaling down in size by the same order over the same period. This period doubling has continued ever since and it shows little sign of stopping, notwithstanding limits posed by the speed of light and other physical constraints. The miniaturisation generated by this evolution reached the point in the last decade where computers were small enough to be embedded into small objects. Combined with sensors which could be deployed extensively within the natural and built environment, they could be used to generate massive volumes of data, second by second and scaled over many locations in real time. Although similar data had been collected quite modestly for many decades using analogue devices, this digital scaling down has given rise to the era of 'big data' which is critical to the development of the smart city movement. Indeed smart cities and big data – and of course the analytics that has developed to make sense of all this – constitute the domain that we will define and describe in this chapter.

There are two quite different perspectives on smart cities. The first and most obvious, some might say superficial, is the actual embedding of hardware and software into the built environment. This represents the focus of the computer industry in all its forms, for the city and its public spaces now constitute a new marketplace for the buying and selling of computers and communications. We will outline the machinery of the smart city which computers offer in the next section but it is important to contrast this with a second perspective which is the impact that computer and communications are having on the social and economic nexus of the city, on the way computers are changing the way cities form and function and on our own behaviour – impacts that are likely to be substantial. This second perspective is a consequence of the first, while the way our behaviour is being changed also affects what we consider appropriate in terms of the hardware and software that we decide constitutes the smart city. To an extent, we might consider the first perspective centred around the impact of computation on the physicality of the city, while the second concentrates on how new technologies are impacting on social and economic structure which is more abstract, but both are interwoven with each other in terms of the smart cities movement. In fact, one of the dilemmas of smart cities is that many groups consider one or the other as the only perspective and often do not relate the two, as we do so in this chapter.

In the rest of this chapter, we will introduce these two perspectives and then focus on a related distinction between the high frequency and low frequency city. Change in cities over very fine time intervals, seconds, minutes, hours, days is high frequency in contrast to changes over years, decades, centuries and so on which is low frequency and there is some correlation between both the physical and the more abstract with respect to these changes. We will then focus on examples of high and low frequencies and suggest that a new, much more extensive science is required to understand the city, based on complexity, simulation and new forms of data mining and perhaps artificial intelligence (AI) or at least machine learning. Our argument slowly turns from more prosaic and realistic tools and methods to softer, more open ideas and speculations and these serve to link these arguments to practical tools to enable us to understand, predict and design future cities (Batty, 2018).

Embedded computation

In automating the city, the most highly constrained behaviours and procedures associated with how the population reacts to routine functions such as movement, the use of energy, everyday marketing such as retailing, repetitive production processes and so on, have always represented the activities that are most likely to be mechanised. Indeed many of these functions were the subject of extensive automation during the first and second industrial revolutions that led to steam power, mechanised routines and electricity. For example, once the automobile was invented, control of the road system using traffic lights, loop counters for assessing traffic volumes, and even control centres based on augmenting human interaction with TV support became routine, coinciding but not yet part of the emerging digital revolution in the mid- to late 20th century. The same kinds of functions emerged for routine marketing and for energy usage with the deployment of cash registers, lighting in cities, more automated waste management and so on. It was fairly obvious that once computers scaled down to the point where they could replace mechanical devices which were intrinsically less reliable and required more maintenance, all these functions would be subject to digital control.

Only since the millennium have sensors linked to digital computers been widely installed, almost simultaneously for card payments in transit, retailing and energy use, with digital replacing analogue in a relatively seamless fashion. With digital sensing, however, vast streams of data monitoring and recording of the operations and usage of these systems have become available. This is 'big data' in the terminology of the current digital revolution, big in the sense that it is voluminous (with its actual volume actually only being determined once the sensors are switched off) and rapid in its delivery – second by second or at finer intervals or more periodic in terms of minute by minute. Much depends on the systems put in place, although raw data can be delivered at a precise instant notwithstanding the fact that it might be delivered to users or to its archives at much less frequent intervals. For example, pollution data in London are made available to the public at large every hour, although it is captured at a much finer temporal interval. In fact digital control, sensing and related services are being introduced into many routine domains within the city and it is virtually impossible to catalogue all of these. Our general view of cities as being entities that are managed, controlled and planned from the top down – which was the collective wisdom of how the city was organised in the mid-20th century, has all but disappeared as the idea of cities evolving from the bottom up has taken root under the banner of complexity theory (Batty, 2005). In such contexts, new information technologies are being introduced to transport, energy, marketing, finance, health care, education – the list is as long as we can count the many functions that define cities in everyday life – and this is why we can never say that one city is any smarter than another. Many of these technologies are invisible or at least, not immediately visible without special scrutiny; they are introduced from the bottom up and thus intrinsically without any central coordination.

Moreover, these new technologies are being introduced without any grand plan, although we can divide them into two kinds. First, there are fixed sensors that can be operated automatically or activated by human touch or sense. That is, sensors that simply record natural and human events that are always switched on, such as pollution monitors and sensors that are only activated by human touch, such as the recording of payments whenever someone makes a tap or swipes a credit card for payment. The second type of sensor is now much more ubiquitous and this is the device that we carry around with us all the time – the smart phone which was introduced in 2007 and then took the world by storm. In fact, much greater volumes of data are being captured using smart phones, by ourselves activating them or their being used as passive sensors. This is a kind of crowd sourcing and much data is being collected this way, some of it being captured by the providers of the services that such phones can activate but a lot being initiated by phone users themselves in social media and related activities.

In another sense, the hard and soft infrastructure of the smart city in terms of computation itself and the communications equipment that is needed to keep our networks up and running, constitutes another physical domain. This also includes the software that enables data to be communicated and computation to be initiated and all of this hardware and software does have physical presence in the great proliferation of fibre optics and data centres which are increasingly visible and use an increasing amount of the world's electricity. To an extent, all this physical plant is relatively unobtrusive, much of it buried underground and built like cities from the ground up. Like the internet itself in terms of the flow of data and information, the network hardware is constructed in smaller pieces or if constituting some global network, is simply one of many, some of which are linked together organisationally but many of which are separate from one another, only linked at key locations for routing and switching (Blum, 2013). To an extent, the provision of all this hardware and software does not appear to be making a major difference to the form of the city but the fact that it is relatively invisible still opens up the possibility that combined with globalisation and changes in human behaviour occasioned by our usage of this technology, there may be profound changes to the physical and spatial structure of cities as this century progresses.

Changing spatial behaviours

If one wishes to understand and predict the physical infrastructure of the smart city within the wider information society, it is essential to abstract and explain the ways this infrastructure is acting on urban populations and the way these populations are organising and reorganising their activities in the city. This constitutes our second focus, involving the way these new infrastructures are impacting on current behaviours, disrupting them, adding dramatically new forms of network to the city, and enabling cities to easily connect up globally, thus facilitating world-wide specialisation as well as new waves of global urbanisation and migration. The hardware and software that we noted in the previous section generates many new kinds of electronic network whose diversity is best seen not with respect to the hardware of the network but in terms of the multiple functions that these networks allow and enable: email to social media to accessing web resources are typical of these new forms of communication that have become significant in the last 30 years.

The smart city is thus based on multiple networks that connect very different kinds of computer together for complex purposes. Prior to the telegraph and the telephone, networks were operated largely by the physical labour of signalling or at best by the middle of the 19th century, by fast transportation, usually stage coach. The telegraph invented round about 1840, the telephone in the late 1880s and television in the 1920s all provided passive networks of communication where users could communicate but not transform or manipulate information. The big breakthrough did not happen until computers were linked to networks that enabled users not only to communicate data and information but manipulate it through enabling computation at a distance. In essence, the computer was an interactive device in stark contrast to earlier information technologies that were largely passive.

To an extent, it is communication *and* computation that defines the smart city and it is connectivity between 'things' and individuals but with individuals enabling the manipulation of 'things' using these new technologies. The Internet of Things (IoT), coined by the Kevin Ashton of Massachusetts Institute of Technology's Auto-ID Labs in 1999, but having a much longer history in terms of ubiquitous computing (see Weiser, 1991), has been popularised by several writers, in particular in the science fiction writer Bruce Sterling's (2005) prescient essays about the potential for communicating between any kind of object within which sensors, computers and their networks might be embedded and linked. It is however the internet that has made all this possible, not only the network of networks in terms of its hardware and software but the very evolution of the net from the bottom up. No one planned it, no one could ever have planned it, but it could have been thwarted had its genesis not been in the public domain, ironically as part of the US cold war effort to share computer resources. By the time the net was truly global it was almost impossible for private capital to take it over and charge for its use. Had this not happened, much of what is now contained within the smart city, through the way we access information using Google and email and social media, would not have occurred, or if it had, it would be in a very different form from the kind of information society that we have today.

The internet revolutionised email and web services but it is also making possible a new kind of economy in which the biggest players exploit the power of the net which is largely costless to access for most users, at least through direct use. What is fast emerging are platforms built around the fact that the internet is free where companies use our ability to connect with anyone, in any place and at any time to exploit this access, thus enabling many different kinds of populations to buy, sell, browse, access, educate, travel – any of a myriad of activities that define the way we interact with one another in modern societies. These platforms are sites/companies/digital forums such as Facebook, Tencent (WeChat), Google, Amazon, Twitter, Alibaba, Baidu, Weibo and so on, as well as the newer more disruptive ones such as Airbnb, Uber and Didi. Their implications are best summed up in Tom Goodwin's immortal opening lines from his article in *TechCrunch* in 2015 when he said:

> Uber, the world's largest taxi company, owns no vehicles. Facebook, the world's most popular media owner, creates no content. Alibaba, the most valuable retailer, has no inventory. And Airbnb, the world's largest accommodation provider, owns no real estate. Something interesting is happening.

The platforms are still emerging very rapidly as we are able to capture more and more information on our devices, have enormous potential to disrupt existing activities in cities and in the economy. Uber is killing some taxi and public transportation services, especially those that serve underprivileged populations that require public subsidies, and Airbnb is taking stock from the housing market that would otherwise serve long term residents who need to rent. Combined with software that is now only accessible on the web and requires extensive password security, it is an open question as to whether or not productivity is beginning to decline because of extensive details needed to simply log on, never mind navigate. During the last 10 years since the Great Recession, productivity in the Western world (and we suspect in China and other parts of Asia Pacific) appears to have been dropping and some of this must be due to the kinds of security that are required to access much information technology. Banks are a good case in point. It is now hard to access bank accounts other than through the web and the security this requires takes a significant proportion of time to initiate and activate. This is a type of disruption from previous practices, discriminating of course against the elderly, the very young and those not able to swing along with the technologies which are getting ever more complex and convoluted. The productivity paradox however is deep-seated and in terms of the smart city seems to conflict with the very idea of introducing automated technologies; we simply flag this as a pointer to the future of smart cities, but we must watch carefully for this area needs substantial research and reflection, just as questions of privacy and confidentiality in all these data services need to be explored with respect to regulation (Goldin, Koutroumpis, Lafond, Rochowicz, and Winkler, 2019).

In 1997, Frances Cairncross popularised the term *The Death of Distance* in her article and book of the same name, articulating what had been clear during much of the industrial revolution. As new movement technologies – railways, automobiles and planes – were invented thus enabling people to travel faster, longer and at lower cost, the role of distance was transformed. Cities were able to get bigger, to grow beyond one million which had been the constraint until the early 19th century, while the non-physical information technologies of the telegraph, telephone and television lowered the friction of distance, enabling people to communicate globally. The invention of the web thus appeared to be the culmination of this process, with there being little need for physical contact if everything could be manipulated digitally. Of course, this was a caricature but the implications were clear. This, Cairncross (1997) argued, represented the 'death of distance', culminating in nearly two centuries of urban growth that might see everyone enriching their activities even further by working, shopping, playing etc. from home. This has not happened over the last 30 years and is unlikely to; big cities have tended to agglomerate even faster with more, not less, face-to-face contact occurring. However what is happening is that urban form is being increasingly disconnected from function and in terms of the smart city, the implications of this have not really been mapped out. In fact, the impact of the death of distance on the hardware and software being introduced into the city, which we noted in the previous section, has barely been considered.

With the majority of the population now connected through hand-held devices, the proliferation of software apps has been dramatic. These range from simple routine tools that enable improved services to much bigger, more fully fledged software applications that can be used on the move to access what once were applications that required a mainframe, a mini or a desktop. In fact a good deal of new software is itself being embedded into the built environment or if not embedded as such, is available on the person through mobile devices which have become essential for many routine activities. The next great wave of change will involve the move to a truly cashless society and the platform companies such as Facebook are already beginning to predict their own development of such media. The development of software *in situ* – code space as Kitchin and Dodge (2011) have called it – is also proceeding apace as the systems to both design and maintain the built, natural and social environment in which we all live are being infected with software which eventually becomes essential for those originally non-digital systems to continue functioning. This is the idea of the 'digital twin', a digital version of the system which begins to merge into the system of which it is a model. Building information models are a case in point and much of the smart city will eventually be composed of such twins, for these are no more nor less than apps that scale to entire areas from individual applications. To elaborate these developments, however, we need to change tack slightly and examine both theory and analytics that enables us to make sense of the contemporary city, particularly the smart city that has introduced many new features into our daily lives that require explanation and understanding if we are to produce effective and equitable designs for the city of the future.

High and low frequency cities

The smart city movement has thrown onto the agenda in stark relief the notion of the 24-hour city. Up until the end of the last century, most of our theories about cities were rooted in thinking of the city as a static entity, largely in an equilibrium that we considered would help us in thinking about how cities might change to a new equilibrium over timespans that were measured in decades or generations. The master plan was the mechanism that would accomplish this through explicit top down planning. The idea of theorising about how we might organise ourselves in the 24 hour city at high frequencies rather than low, although implicitly considered through routine management, was largely absent from our arsenal of theories and methods. Lack of temporal data was as much a cause of this dilemma as any lack of thinking about how cities changed over all spans of time from the shortest to the longest. The development of scaled-down sensors, the vast proliferation of network technologies and tiny computers has changed all this. In the last 30 years, many systems to monitor what happens in cities over very fine time scales have been put in place.

The other change has been in the way we think about urban dynamics. No longer is the idea of the city in equilibrium credible. Cities are manifestly systems in disequilibrium, always, and thus equilibrium is a simplification too far. In fact cities are often thought about as far-from-equilibrium, which is the concept adopted by complexity science in which systems like cities evolve from millions of individual and group actions, all originating from the bottom up (Batty, 2017). If cities evolve in this way, then their dynamics are on all scales, from the smallest to the largest and in this sense, the high frequency merges into the low frequency city. However most of our understanding based on formal and systematic models is very strongly physical in focus. Basically we still think of cities as being forms that follow function, despite the fact that this mantra was only ever useful as an analogy in emergence of the modern movement in the late 19th century and it is now very wide of the mark. Most of our analytics is thus based on methods of spatial analysis which are statistically based on regularities in land use, activities and transportation in cities, on demographic and employment location, while more formal models explaining how housing markets are structured are still used to think about the way populations locate and the way residential development takes place. These ideas come from social physics and urban economics but some of them are increasingly passé.

The changes that have made many of these theories, established from the middle of the last century, somewhat redundant and obsolete, relate to the fact that cities have become ever more complex over the last 200 years and the increase in their complexity shows no sign of stopping. The smart city movement thus sits on top of all the evident complexity that had emerged physically, involving the decentralisation of jobs, agglomeration of financial functions in central business districts, urban sprawl, continuing migration and globalisation. Our tool box of techniques and models which constitute urban analytics is now beginning to include methods that deal with the 24 hour, high frequency city, for we now have data that enable us to find patterns at fine temporal scales; the heterogeneity that is uncovered when we move from aggregate to disaggregate, and from equilibrium to disequilibrating change can now be disentangled using a variety of multivariate techniques that are being continually refined as we learn more about urban dynamics across these scales.

The wide range of tools that are becoming available to enable us to make sense of cities build on methods that have been established over many years certainly since the 1960s but to an extent, from the late 19th century when location theory and social physics began to emerge. From these theoretical ideas about how cities are structured in terms of the location of activities and land uses and the ways in which transportation patterns become established came a flurry of computer models beginning in the 1950s in the United States, where the focus was very largely on transportation systems which were then being developed to cater for the automobile and the construction of the interstate highway system. These computer models met with only partial success in that theory was limited, data were sparse and incomplete, computational power was never enough and the focus on using such models to address contemporary urban policy problems was minimal. Nevertheless, new generations of model were built around different approaches emphasising dynamics, land development and disaggregate behaviour as well as non-equilibrium perspectives. By the time the smart city emerged in the early 21st century, the arsenal of techniques included land use transportation interaction (LUTI), agent-based (ABM), cellular automata (CA) and micro-simulation models, along with many well developed approaches to spatial analysis built around appropriate applications of spatial statistics and econometrics.

However, much of this heritage is in the spirit of building models that are deductive and predictive, whereas the emergence of big data from highly routinised fine scale temporal processes requires tools to extract patterns from such data and models built on these patterns which tend to be pragmatic and hence much less reliant on theory than previous generations of techniques. So far, despite considerable hype about data mining, deep learning and the power of neural nets in building predictive models for pattern recognition and prediction, there are few examples of how these tools can be used in urban analytics for the smart city. In the next section, we will recount experiences with exploring big data sets in cities, particularly in transit, where potentially there are some interesting and insightful patterns to be mined but our ability to explain these without powerful theory is quite limited. There is little doubt that highly routinised processes such as those that pertain to traffic movements of various kinds from cars to trains, might be automated using patterns that pertain within highly constrained situations, and examples of traffic control already exist from previous times when analogue systems were first developed. The promise of autonomous vehicles depends on our assumptions that such regularities can be extracted from massive amounts of data pertaining to the driver experience and the surrounding environment, and although the tests so far appear promising, coping with very complex environments will be a real challenge.

These kinds of automation are of the simplest kind but when it comes to much more complex behavioural structures in cities involving housing markets, the location of financial services, the provision of transport infrastructure, questions of heritage and preservation and a whole range of issues pertaining to location and interaction in cities, the kinds of analytics we require are not very different from those that pre-date the smart city. As we have noted, these theories and tools require substantial work if they are to be used intelligently to manage and plan the city over any time scale, and the fact that cities are becoming more complex and our focus has extended to embrace the much higher frequency city has simply increased the challenge of developing good science for a much more profound understanding than anything hitherto. Our theories, which in the past pertained to the low frequency city, need to be extended to the high frequency and this requires a continuum of data from the shortest temporal scales to the longest and from the finest spatial scales to the coarsest. This is a continuing dilemma that shows little sign of abating and perhaps it heralds an era when we need to accept that we will need to keep running to stand still, which may well be an intrinsic characteristic of post-industrial, digital cities and the society therein.

Big data in the smart city

A crude definition of big data is 'anything that will not fit in an Excel spreadsheet'. As these sheets have reached a million rows, then it might be argued that if you had a million items of data with a much more modest number of attributes, say 256 or 1024, then you would find it difficult to pack these into such a sheet anyway, but the point is that data greater than such volumes require special software and tools to deal with it in terms of storage, retrieval and analysis. For example, in my research group,[1] we have a dataset from Transport for London consisting of all the tap-ins and tap-outs ('taps') for all passengers using the Oyster card – the Radiofrequency Identification (RFID) card (or equivalent) that were used for payment on all public transport in Greater London – that is nearly one billion taps (rows if you like) for three months from July to September in 2012 (Reades, Zhong, Manley, Milton, and Batty, 2016). This is big data by our standards; it is comprehensive and accurate, although such data are often incomplete in that sometimes the tap-ins and tap-outs are not captured by the system, if the barriers are left open occasionally (as they are in some stations) and if the traveller does not need to validate their payment due to their having a free card or season ticket.

Such data in principle then give all movements between origin and destination stations on the rail network where both tap-ins and tap-outs are required but the actual paths between these stations – the flows of traffic – need to be constructed using various shortest route algorithms which are by no means perfect in that travellers do not always follow their shortest route for many reasons involving cognition, navigation, travel preferences and so on. Nevertheless the matrix of trips is as complete as possible, notwithstanding that external data, for example, from questionnaire surveys might be used to enhance it. However, integrating this dataset into the set of data needed to examine the wider pattern of travel is highly problematic. Origins and destinations at stations for example are only part of the story in that what we need to explore overall movements are the trips that are made before the traveller enters the station and the trips when the traveller exits it. In short we need to 'add value' to the data, synthesising it with all the other movements that the traveller in question makes. In the absence of such data, the problem is incomplete in that the data are limited. In fact, it is hard to know how such data might be used in understanding the overall pattern of trips by rail, and when the problem is scaled to all trips, these problems become ever more severe. This does not mean that insights cannot be generated from the analysis of such data even though it is partial data. We can explore such data with respect to disruptions to the system from which we can extract how people behave if a rail line goes down due to stalled trains or signal failures, working out the cascades onto other lines and out of the system. Because there is no tap-out on a bus, only a tap-in, there are limits to exploring multimodal travel on rail and bus. We can however examine the pattern of travel with respect to the very limited set of attributes in the data – such as the kind of card: child, elderly and so on – noting spatial variations in travel demand and tying this to other datasets such as that involving geo-demographics from the Population Census and such databases. This can give some insights into patterns in the data but the extent of analysis is still quite limited.

If you think of these kinds of problems writ-large across the city for all the big datasets that are now being collected, the scale of the challenge becomes quite evident. Big data generated routinely in real time is only as good as the attributes that are tagged in such recording and very often there is no common key, other than locational or temporal, that enables data to be stitched together. Even if data can be linked with a locational referent or temporal index, this does not necessarily enable any cross-classification, and the datasets thus have limited applicability. When one turns to other data that are potentially big, such as mobile phone records which it is suggested correlate with travel patterns and from which it appears that travel patterns might be extracted, then the problems are even greater. Mobile phone calls are tagged to cell towers, and even on the assumption that such calls are tagged to the nearest tower (which is not necessarily the case), a very brave assumption is required that such data are correlated with actual traffic patterns. As with transit smart card data, much of the analysis of such data is exploratory and although there are interesting features and patterns that might be extracted, it is still an open question as to how useful such data might be for transport planning.

Despite all the hype about the smart city and the generation of big data from networks of sensors that are likely to be installed everywhere, none of this has resolved the basic problem that faces us in our understanding of cities and the means we have to predict and design their future. These are age-old problems compounded by the fact that cities are getting more complex, of which the smart cities movement and the embedding of technologies into the city are part and parcel but only one part of this increasing complexity. The notion proposed by Anderson (2008) that we no longer need theory and that all will be revealed in big data is incredulous and it is more than 10 years since he wrote this. During that time, there has been very little progress with respect to the development of new ideas coming from pattern recognition in big data. Most of what has been developed is highly routinised information technologies being embedded into what were once entirely mechanical systems such as cars, traffic lights and so on. One can never say that eventually new theory and analysis will not emerge from big data, for if we know anything, we know that the future in unknown and unpredictable, but perhaps even more so in an era when the speed at which inventions and innovations are taking place is continuously accelerating (Kelly, 2016).

Conclusion

The smart cities movement, and we call it a movement because it is so wide in scope, is being used as a label to cover a variety of opinions and ideologies about the city. These range from the provision of new information technologies being embedded into cities by the private sector that supply computer networks and software all the way to those who consider the major issues in cities to be problems of sustainability, regeneration, improving the quality of the environment and many of the traditional concerns of urbanists, planners and politicians who have a concern for creating a better life. In this chapter, we have argued that the smart city must be seen in terms of urban dynamics that cover all temporal and spatial scales, not just the 24 hour city that is dominated by big data, sensing and the generation of real time data but by the low frequency city.

Our argument that the tools we have been developing for the last half century need to be reinvigorated rather than replaced with inductive pattern seeking in the manner of machine learning and data mining, does not imply that there is no place for these new approaches but that they must complement and supplement rather than substitute for our current arsenal of techniques. The chapters in this book show how diverse the range of theories, ideologies, methods, models and tools to tackle the problems of the contemporary city are. What is required is a much more focused effort on adapting these tools to new circumstances, and this chapter has sketched some of the new directions in which this quest might proceed.

Note

1 Centre for Advanced Spatial Analysis (CASA) at University College London (UCL).

References

Anderson, C. (2008) The end of theory: The data deluge makes the scientific method obsolete, *Wired*, 23rd June, www.wired.com/2008/06/pb-theory/

Batty, M. (2005) *Cities and Complexity: Understanding Cities with Cellular Automata, Agent-Based Models, and Fractals*, MIT Press, Cambridge, MA.

Batty, M. (2017) Cities in Disequilibrium, In Johnson, J., Nowak, A., Ormerod, P., Rosewell, B., and Zhang, Y.-C. (eds) *Non-Equilibrium Social Science and Policy: Introduction and Essays on New and Changing Paradigms in Socio-Economic Thinking*, Springer, New York, 81–96.

Batty, M. (2018) *Inventing Future Cities*, MIT Press, Cambridge, MA.

Blum, A. (2013) *Tubes: Behind the Scenes at the Internet*, Penguin Books, New York.

Cairncross, F. (1997) *The Death of Distance: How the Communications Revolution Is Changing Our Lives*, Harvard Business School Press, Cambridge, MA.

Goldin, I., Koutroumpis, P., Lafond, F., Rochowicz, N., and Winkler, J. (2019) Why is productivity slowing down? www.oxfordmartin.ox.ac.uk/downloads/academic/201809_ProductivityParadox.pdf

Goodwin, T. (2015) The battle is for the customer interface, *Techcrunch*, 3rd March, https://techcrunch.com/

Kelly, K. (2016) *The Inevitable: Understanding the 12 Technological Forces That Will Shape Our Future*, Penguin Books and Random House, New York.

Kitchin, R., and Dodge, M. (2011) *Code/Space: Software and Everyday Life*, MIT Press, Cambridge, MA.

Moore, G. (1965) Cramming more components onto integrated circuits, *Electronics*, 38, 8, April 19, 114–117.

Reades, J., Zhong, C., Manley, E., Milton, R., and Batty, M. (2016) Finding pearls in London's oysters, *Built Environment*, 42, 3, 365–381.

Sterling, B. (2005) *Shaping Things*, MIT Press, Cambridge, MA.

Weiser, M. (1991) The computer for the 21st century, *Scientific American*, 265, 94–104.