Appl. Spatial Analysis
https://doi.org/10.1007/s12061-018-9258-6

The Future of Urban Modelling

Alan Wilson [1,2]

Received: 28 March 2018 / Accepted: 26 April 2018
© The Author(s) 2018

Abstract The future of urban modelling is viewed first against a background of its fifty-decade history. The effects of increased computing power and the availability of new data sources are explored, particularly through a wider range of scales and applications – illustrated by global scales and applications as wide-ranging as defence and security and history and archaeology. The challenges of making models fully dynamic are articulated along with a recent development which introduces uncertainty into dynamic urban models through a potential function. Finally, the potential for more effective deployment of models in city planning is shown with a system that combines data assembly, modelling and interactive planning.

Keywords Urban modelling · Dynamics · Defence · History · City planning

Introduction

Urban modelling has a long history and this provides the platform for thinking about its future. Its origins go back at least as far as Malthus and von Thunen and then via Christaller and Losch to the advent of computers in the 1950s. The latter was a turning point – fuelled by the need for transport models to help drive the highway building programme in the United States. The path into comprehensive modelling was led by Lowry in 1964 with his *Model of Metropolis* – still to be seen as a major landmark and ongoing influence. We had available, from various perspectives, a good spatial interaction model toolkit – critical, since a crucial part of modelling the city meant modelling flows of all kinds.

✉ Alan Wilson
a.g.wilson@ucl.ac.uk

1 The Alan Turing Institute, 96 Euston Rd, Kings Cross, London NW1 2DB, UK

2 Centre for Advanced Spatial Analysis, University College London, 1-19 Torrington Place, London WC1E 7HB, UK

Published online: 08 May 2018

The models were, in the main, equilibrium comparative-static models. From the late 1970s, on a slow burn, progress was made with modelling the 'slow dynamics' – the evolution of urban structure. This remains important, but is still a slow burn. As computing power increased, new methods became feasible, including microsimulation, cellular automata, network analysis, and perhaps most important of all, agent-based modelling. Much of this progression can be seen as involving different ways of making the inevitable approximations to handle the real-world complexity of city regions. The history is well documented – see, for example, Wilson (2012) and Wilson (2013) for a compendium of papers which together describe this. What follows is very largely illustrated from the recent work of myself and colleagues.[1]

In the rest of this paper, we look ahead to the likely – possible? – futures of urban modelling. As in earlier periods, but yet again, there is a sea change occurring in terms of data availability and in computing power – in the latter case, both hardware and software. We have a substantial platform on which to use this new data and computing power to 'make the best of what we have'. There are huge opportunities under this heading alone, and we pursue this in the second section. There are particular opportunities to deploy the methods of urban modelling in new areas, often through excursions into disciplines where the methods are relevant but have been largely untouched by these possibilities. We give some examples in the third section. We might also anticipate the acceleration of the slow burn of research on dynamics and we explore the possibilities in the fourth section. There is a potential significant new development to which we draw attention here. In the penultimate section, given that approaches to urban modelling are diverse, this provides opportunities to 'finish off the theory' and to integrate across paradigms. Finally, we speculate about the future uses of urban modelling. The motivation for urban modelling has always been to integrate fully into city and regional planning. Some progress has been made, but the biggest opportunities lie in the future.

Making the Best of it: Data and Computing Power

The Data Challenge

We have noted the increasing availability of new data sources – from sensors, mobile phones, administrative data to name a few – the so-called 'big data' revolution. Models provide a conceptual framework for thinking through data needs – whether for research or for planning reasons. Our use of data should be purposeful. There is then an immediate research challenge: to provide adequate architecture for a supportive data system. This would have uses in its own right coupled with good visualisation software – for example, to construct 'narratives' detailing urban challenges. In many ways, it can be argued that this is what GIS systems offer, but there is a possibility that a data system rooted in modelling may be more effective.

[1] This paper was presented at a conference which, in part, celebrated the fiftieth anniversary of the publication of my first entropy-maximising paper (Wilson 1967).

Sector Models, Comprehensive Models

Urban modelling has been most developed in its sector applications – notably transport and retail. These sorts of applications will no doubt continue, increasingly built and deployed by users rather than researchers. The need for comprehensive models remains, however, not least because of the obvious interdependencies between sectors – and these must be handled to avoid unforeseen consequences in planning applications. A small band of researchers have maintained the field but, with luck, future demands will facilitate growth. Challenges remain for routine integration of known submodels – for example, spatial demographic and input-output models. One comprehensive modeller to do this is Simmonds and his colleagues – see Simmonds (1999, 2013). Computing power is such that these models can be built on wider spatial scales – the Quant model for example embraces most of the UK (Batty et al. 2013) – and can, in principle, represent sector submodels in all available detail. This makes possible a future in which, in the UK for example, a national model can be made available which can be used for both planning and commercial users for a variety of purposes. Is it a role for government to provide this, or the commercial sector?

Extensions

The skills at the core of urban modelling, particularly representing spatial interaction and structural dynamics, have wider applicability than is customarily deployed. Even in cases where researchers have spatial interaction features, in economics for example, there are still many cases where a 'gravity model' and log-linear regression is used. In the following subsections, we illustrate, from recent work, applications resulting from: adding new sectors; changes of scale; a different field of study for urban modellers: defence and security; and venturing into other disciplines, and in this case time periods – history and archaeology.

Adding New Sectors

Urban modelling has developed very much in the context of applications for which the models were often designed – and hence the focus on transport, retail, housing and urban form. There are now particular concerns with sustainability and hence with energy use, and with the polluting effects of various activities. It is relatively straightforward to estimate the demand for energy for residential and business areas; it is more difficult to model the supply flows – in the case of electricity for example, connecting generation, the National Grid and the variety of suppliers. So we should seek to add all the utilities, including telecoms and broadband to our comprehensive model of a functioning city. First steps are being taken in this direction in the exploration of a digital twin for the National Infrastructure Commission.

A World Model

There are many global challenges that require appropriate models to underpin relevant analytics: migration, trade, security and development aid, for example. These four areas were explored in a recent **Engineering and Physical Sciences Research Council** (**EPSRC**) project, sector by sector, but also with the ambition of building a comprehensive model. The spatial zone system was made up of 220 countries and the project illustrates the value of proof-of-concept approaches to modelling research – in this case because of the variable quality of the available data. In order to be effective, a set of input-output economic accounts are needed for each country. Excellent data are available for 40 countries. The rest were estimated by looking for similarities of structure combined with some known production totals and international trade flows (Oleron-Evans and Levy 2016). In the end, an integrated model was produced (Levy et al. 2016). However, many of the methods were deployed at regional scales (still with 'country' zones) and the results are presented in Wilson (2016a, b).

Sea- and Land-Locked Countries

The skills acquired in modelling trade flows were deployed in a World Bank study where the objective was to improve trade flows in sea-locked and land-locked countries. For the sea-locked case, an international trade model for the South Pacific Island Countries (SPICs) was used (Caschili et al. 2015) to test alternative scenarios of port hubs and shipping routes: a different kind of planning. For the land-locked case, Uganda was used as the example. The challenge here was to explore ways of speeding up the flow of farm crops to Entebbe airport. This was a more micro-scale study within which the detailed functioning of markets were explored using an agent-based model to trace the flows. These studies are published in Medda et al. (2017).

Defence and Security

Recent studies in defence and security – the latter to include policing as well as military – have been stimulated by an interest in the Lotka-Volterra equations in ecology and their relationship to the Harris-Wilson model of retail dynamics. In ecology, these equations represented either prey-predator or competition-for-resources systems. The similarity with, for example, dynamic retail models, arises because retailers can be seen as competing for consumers. The original Lotka-Volterra equations had no spatial dimensions. The retail equations looked like Lotka-Volterra equations with space, and indeed were modelled in these terms (Wilson 2006). Richardson (whose papers were collected posthumously in Richardson 1960) had in the 1930s famously used the aggregate equations to model an arms race and this opened the possibility of using spatially-disaggregated Lotka-Volterra equations in a defence and security context. There was then a crucial conceptual step: to interpret spatial interaction as 'threat'. This enabled the development of spatial Richardson models which could, in principle, be deployed at a variety of scales – say from the battlefield (Baudains et al. 2016a) to the urban through the regional to the global (Baudains et al. 2016b). These ideas were tested in a variety of contexts: the London riots (Davies et al. 2013), piracy in the Gulf (Marchione et al. 2016; Marchione and Wilson 2016) and the disposition of military forces in North and South Korea.

History and Archaeology

Urban modelling has largely been applied in more or less contemporary contexts. There is an obvious opportunity to apply the same methods for historical periods and this has the potential to offer major impacts in history and archaeology. There was early work in the 1980s to use a modified retail dynamics model to estimate settlement sizes in Ancient Greece – where settlement locations were known, but much less about size (Rihll and Wilson 1987). These methods have been further developed more recently through further work on Greece and Crete (Bevan and Wilson 2013) and on the Assyrian Empire (Davies et al. 2014). In the latter case, this has been further extended to model military dynamics (Baudains et al. 2015). A related approach has been used to model the evolution of the urban system in North America in the nineteenth century – particularly in relation to the development of railways (Wilson and Dearden 2011).

Dynamics

Building on the Foundations

Spatial interaction modelling can be considered to be concerned with the 'fast dynamics': in effect, it suffices to model equilibrium flows because it is a reasonable assumption that, following a change – say the introduction of a new rail line – the system will return to equilibrium very quickly. This is not true for the evolution of urban form and infrastructure of all kinds. Some considerable insight was offered by the Harris and Wilson (1978) paper on retail system dynamics. Progress has been slow. There are now proof-of-concept studies to show how these insights can be interpreted and deployed. For example, the analysis can be used to estimate the minimum size of a new retail centre for it to 'succeed' – that is to achieve a stable and positive equilibrium size (Dearden and Wilson 2015). It is more challenging to carry out similar analyses for transport networks but some progress has been made (de Martinis et al. 2014). The next step is to incorporate full dynamics into comprehensive models. This has been done in Dearden and Wilson (2015). It becomes possible then to identify new kinds of criticality – for example, the tipping point which represents gentrification.

Solving a Big Problem?

In the paper so far, the argument, for the future, has been concerned as much with model refinement and opportunities for application (and more of each to come) than with new mathematics. Here, a new result is introduced which could be of considerable importance – from Ellam et al. (2018). The challenge is this: while we can estimate equilibrium values of (for example) a vector of retail centre sizes, {Wj}, we know nothing about the probability distribution of the whole configuration. The Harris and Wilson core equation is:

$$dW_j/dt = \varepsilon\left[D_j(\underline{W}) – KW_j\right] \tag{1}$$

If we now represent W = {W_j} as a vector of random variables, X, we can generalise (1) into a stochastic framework to which we can add (Brownian) noise. To achieve this, we define a potential function V(X) so that the differential equation for X is:

$$dX = -\nabla V(X)dt + \sqrt{2\gamma^{-1}}dB, \quad X(0) = x \qquad X = \{Wj\} \tag{2}$$

where

$$-(\nabla V(x))_j = \epsilon \Pi_j(x) = D_j(W) - \kappa W_j, \quad j = 1, \ldots, M \tag{3}$$

showing the embedding of the Harris-Wilson equation. A suitable potential function can be shown to be:

$$\epsilon^{-1}V(x) = \underbrace{-\sum_{i=1}^{N} \alpha^{-1} O_i \ln \sum_{j=1}^{M} \exp\left(\alpha x_j - \beta c_{ij}\right)}_{Utility} + \underbrace{\kappa \sum_{j=1}^{M} w_j\left(x_j\right)}_{Cost} - \underbrace{\sum_{j=1}^{M} \delta_j x_j}_{Additional} \tag{4}$$

where

$$w_j\left(x_j\right) = \exp x_j, \quad j = 1, \ldots, M \tag{5}$$

Equation (2) can then be rewritten as:

$$dW_j = \epsilon W_j\left(D_j(W) - \kappa W_j + \delta_j + \frac{\sigma^2}{2}\right)dt + \sigma W_j dB_j, \quad j = 1, \ldots, M \tag{6}$$

From this formulation π(W), the probability distribution of W occurring, and its evolution path, can be generated. This opens up a new field of research which might even produce a long-awaited derivation of Zipf's Law!

An Integrated Theory: Crossing Paradigms?

When there are alternative approaches in a field like urban modelling, given that each approach is focused on the same system of interest, it is potentially valuable to pose the questions: why, and can they be integrated? Some differences arise because disciplinary tool kits are brought into play: economists, for example, will work with equilibrium neo-classical frameworks. They are also inclined to work with continuous rather than discrete variables in their models, and this points us towards the second source of differences: different ways of making approximations to make the model-building of a system as complex as a city feasible. In this instance, the economists almost certainly made the wrong design decision as the mathematics is more tractable with discrete variables for urban modelling.

It is possible to analyse the approaches in a systematic framework that then potentially facilitates integration. We have a well-defined system of interest: the city.

We can ask what we know as a theory of the city – how cities 'work' and evolve. We need to bring all sources of knowledge to bear on this: economics, sociology, geography, psychology, political science and more. And hence to state the theory fully, we need to be interdisciplinary - see Wilson 2010 for a more extended argument - and to force integration in this respect. It is no use, for example, assuming that all individuals have perfect information and can determine their behaviour by optimising a utility function. We can then tackle the second issue by asking the question: given our knowledge of theory, what methods can we use to represent that theory in a model? There are many partial answers to these questions but the force of the argument here is that this mode of thinking is worth much more effort!

Optimising Uses

Figure 1, from Roumpani et al. (2014), shows how a model can be fitted into a wider planning framework.

The usefulness of models in city planning – which can be viewed in a broad sense to include all aspects, e.g. including economic development, beyond traditional town planning – has been contested at various times. The key is to be able to understand what models can achieve in this context. In many instances, they are very good at short-run forecasting. But we then understand, both intuitively and technically – in relation to nonlinear complex systems – that they cannot deliver accurate long-run forecasts. What they can do for the longer run, is be used to explore the workings of alternative planning scenarios and in this context they can also be invaluable (see Wilson 2016c).

Concluding Comments

In this issue, we are celebrating the fiftieth anniversary of the publication of 'A statistical theory of spatial distribution models' (Wilson 1967) and a forthcoming fortieth anniversary of 'Equilibrium values and dynamics of attractiveness terms in production-constrained spatial-interaction models' (Harris and Wilson 1978). We have

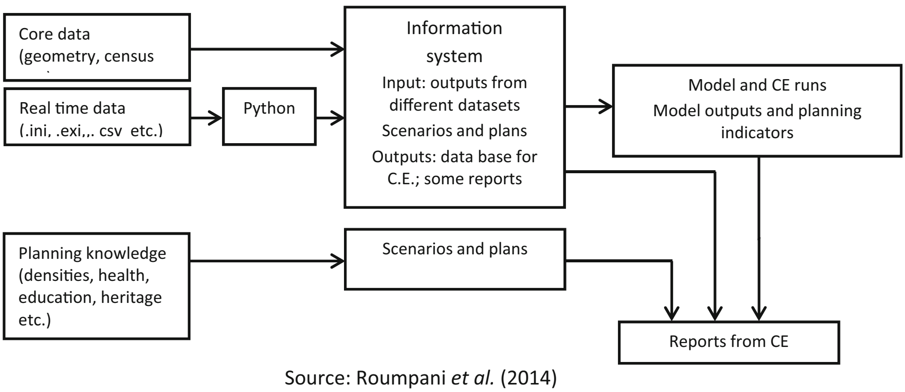

Fig. 1 Embedding data capture and models into an interactive planning system

demonstrated that there is plenty of life left in spatial interaction modelling and significant research challenges, basic and applied, when spatial interaction models are combined with dynamic models.

There is scope for theoretical research, particularly on dynamics and integration across disciplines – to make urban modelling truly interdisciplinary. There is tremendous scope for a much wider range of applications – in particular disciplines such as history but most of all in the practicalities of planning. It is in this latter case that, given data sources and contemporary computing power, there is scope for a serious government initiative to make urban modelling capability widely available. The Quant model can be seen as a pilot for this.

Open Access This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.

References

Batty, M., Vargas, C., Smith, D., Serras, J., Reades, J., & Johansson, A. (2013). SIMULACRA: Fast land-use–transportation models for the rapid assessment of urban futures. *Environment and Planning B, 40*, 987–1002.

Baudains, P., Zamazalová, S., Altaweel, M., & Wilson, A. G. (2015). Modeling strategic decisions in the formation of the early neo-Assyrian empire. *Cliodynamics: The Journal of Quantitative History and Cultural Evolution, 6*(1), 1–23.

Baudains, P., Davies, T.P., Fry, H. M. and Wilson, A.G. (2016a) From colonel blotto to field Marshall blotto, in Wilson, A. (ed.) 2016-B, Wiley, Chichester, pp. 283–292.

Baudains, P., Fry, H. M., Davies, T. P., Wilson, A. G., & Bishop, S. R. (2016b). A dynamic spatial model of conflict escalation. *European Journal of Applied Mathematics, 27*(3), 530–553.

Bevan, A., & Wilson, A. G. (2013). Models of settlement hierarchy based on partial evidence. *Journal of Archaeological Science, 40*(5), 2415–2427 Available at: https://doi.org/10.1016/j.jas.2012.12.025.

Caschili, S., Medda, F. R., & Wilson, A. G. (2015). An interdependent multi-layer model: resilience of international networks. *Networks and Spatial Economics, 15*(2), 313–335.

Davies, T., Fry, H., Wilson, A. G., & Bishop, S. R. (2013). A mathematical model of the London riots and their policing. *Nature Scientific Reports, 3*, 1303.

Davies, T., Fry, H., Wilson, A. G., Palmisano, A., Altaweel, M., & Radner, K. (2014). Application of an entropy maximizing and dynamics model for understanding settlement structure: The Khabur Triangle in the middle bronze and Iron ages. *Journal of Archaeological Science, 43*(March), 141–154.

de Martinis, V., Pagliara, F., & Wilson, A. G. (2014). The evolution and planning of hierarchical transport networks. *Environment and Planning. B, Planning & Design, 41*(2), 192–210.

Dearden, J., & Wilson, A. G. (2015). *Explorations in urban and regional dynamics*. Abingdon: Routledge.

Ellam, L., Girolami, M., Pavliotis, G. & Wilson, A. (2018). Stochastic modelling of urban structure. *Proceedings A, Royal Society*. https://doi.org/10.1098/rspa.2017.0700.

Harris, B., & Wilson, A. G. (1978). Equilibrium values and dynamics of attractiveness terms in production-constrained spatial-interaction models. *Environment and Planning A, 10*, 371–388.

Levy, R. G., Oleron Evans, T., & Wilson, A. G. (2016). A global inter-country economic model based on linked input-output tables. In A. G. Wilson (Ed.), *Global dynamics: Approaches from complexity science* (pp. 51–72). Chichester: Wiley.

Lowry, I.S. (1964) A model of metropolis, *Memorandum RM-4035-RC*, The Rand Corporation, Santa Monica. Available at: https://www.rand.org/content/dam/rand/pubs/research_memoranda/2006/RM4035.pdf

Marchione, E., & Wilson, A. (2016). Spatial interaction as threat: Modelling maritime policy. In A. G. Wilson (Ed.), *Global dynamics: Approaches from complexity science* (pp. 187–194). Chichester: John Wiley.

Marchione, E., Johnson, S. D., & Wilson, A. (2016). Agent-based models of piracy. In A. G. Wilson (Ed.), *Approaches to geo-mathematical modelling: New tools for complexity science* (pp. 217–236). Chichester: Wiley.

Medda, F. R., Caravelli, F., Caschili, S., & Wilson, A. (2017). *Collaborative approach to trade: Enhancing connectivity in sea- and land-locked countries*. Heidelberg: Springer.

Oleron-Evans, T., & Levy, R. G. (2016). A method for estimating unknown national input-output tables using limited data. In A. G. Wilson (Ed.), *Approaches to geo-mathematical modelling: New tools for complexity science* (pp. 51–68). Chichester: Wiley.

Richardson, L. F. (1960). *Arms and insecurity.* Pittsburgh: The Boxwood Press.

Rihll, T. E., & Wilson, A. G. (1987). Spatial interaction and structural models in historical analysis: Some possibilities and an example. *Histoire & Mesure, II-1*, 5–32.

Roumpani, F., Hudson-Smith, A., & Wilson, A.G. (2014). RIBA think piece series–digital planning: ideas to make it happen, http://issuu.com/ribacomms/docs/riba_think_piece_series_-_digital_p?e=2663058/7886017

Simmonds, D. (1999) revised 2013, The design of the DELTA land-use modelling package, *Environment and Planning B*, 26, 665-684; revised version in Wilson, A.G. (ed.) *Urban modelling: critical concepts in urban studies. 5 Volumes*, Routledge, Abingdon, volume 5, pp. 59–92.

Wilson, A. G. (1967). A statistical theory of spatial distribution models. *Transportation Research, 1*, 253–269.

Wilson, A. G. (2006). Ecological and urban systems models: some explorations of similarities in the context of complexity theory. *Environment and Planning A, 38*(4), 633–646.

Wilson, A. G. (2010). *Knowledge power: Interdisciplinary education for a complex world*. Abingdon: Routledge.

Wilson, A. G. (2012). *The science of cities and regions: Lectures on mathematical model design*. London: Springer.

Wilson, A. G. (Ed.). (2013). *Urban modelling: Critical concepts in urban studies* (Vol. 5). Abingdon: Routledge.

Wilson, A. G. (Ed.). (2016a). *Global dynamics: Approaches from complexity science*. Chichester: John.

Wilson, A. G. (Ed.). (2016b). *Approaches to geo-mathematical modelling: New tools for complexity science*. Chichester: Wiley.

Wilson, A. G. (2016c). New roles for urban models: Planning for the long term. *Regional Studies, Regional Science, 3*(1), 48–57.

Wilson, A. G., & Dearden, J. (2011). Tracking the evolution of regional DNA: The case of Chicago. In M. Clarke & J. Stillwell (Eds.), *Understanding population trends and processes* (pp. 209–222). Berlin: Springer.