Agent-Based Modelling for Urban Planning Current Limitations and Future Trends

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Abstract. With the global population expected to increase form 7.3 billion in 2015 to 9.5 billion by 2050 [41], smart city planning is becoming increasingly important. This is further exasperated by the fact that an increasing number of people are relocating to cities as we live in a highly urbanised world. Cities are evolving in complex and multidimensional ways that can no longer be limited to land use and transport development. In increasingly important that cities planning embraces a more holistic, participatory and iterative approach that balances productivity, livability and sustainability outcomes. A new generation of bottom up, highly granular, highly dynamic and spatially explicit models have emerged to support evidence-based and adaptive urban planning. Agent-based modelling, in particular, has emerged as a dominant paradigm to create massive simulations backed by ever-increasing computing power. In this paper we point at current limitations of pure bottom-up approaches to urban modelling and argue for more flexible frameworks mixing other modelling paradigms, particularly participatory planning approaches. Then, we explore four modelling challenges and propose future trends for agent-based modelling of urban systems to better support planning decisions.

Keywords: Agent-based modelling · Key challenges · Urban modelling · Urban planning

1 Introduction

Over the last 50 years, urban planning has drastically evolved from a traditional top-down and linear process of survey-analysis-plan to a more integrated and inclusive approach whereby cities are considered as systems of increasingly

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interconnected parts (Chadwick, 1971, cited in [15] p. 3). This evolution coincides with the transformation of modern cities into evermore complex organisms in which social, material and information flows grow always faster while relying on infrastructure systems characterised by stronger inertia. Samuel Arbesman describes this clumsy though functional patching as an urban 'kludge' [1]. In this context, comprehensive monitoring of cities to better inform planning has led to the broad appeal of so-called 'smart cities'. However, a fully comprehensive monitoring of cities has proved to be unrealistic to date, leading Couch ([15], p. 4) to suggest an alternate strategy inspired by Etzione whereby a mixed-scanning approach allows for a light touch routine monitoring able to detect abnormalities justifying more detailed urban investigations.

Since the early 50s, urban planners have increasingly relied on models to better understand and predict the consequences of urban policies on land use, transport and people's wellbeing. Batty [6] suggests that successive urban modelling paradigms can hardly be dissociated from their object (city), purpose (planning) and inputs (data) ; thus, this "intersecting time line" implies that urban models are strongly history-contingent and context-dependent metaphors (Fig. 1). For example, centralised urban planning backed by strong market drivers characterised the 60s and partly explained the reliance on static macro-economic models. In contrast, current best practice urban planning is driven by bottom up participatory approaches and thus bottom up CA and thus bottom up agent based modelling provide a suitable support modelling paradigm.

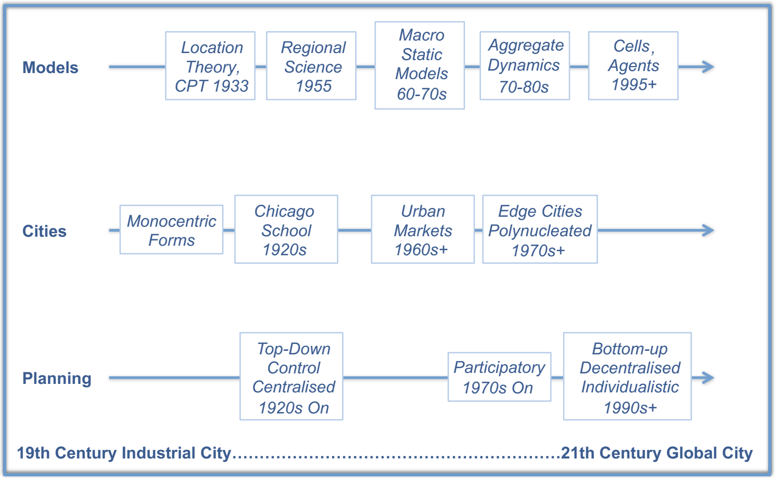

Fig. 1. Intersecting models, cities and planning time lines, reproduced from [6]

2 Current Limitations in Urban Modelling

This evolution suffers from various imperfections, as these timelines are loosely synchronized the intensity of synchronisation depending on theoretical advances in planning and modelling, as well as technological ones in urbanism and computing. This issue was first identified by Lee in his famous requiem [25] and analysed by Michael Batty [5] twenty years ago: the major reasons for lack of practical applications, in our view, are the volatility of the problem context that planning addresses and our inability to develop tools sufficiently robust to withstand such shifts in viewpoint ([5], p. 7). Despite significant computing advances this was still an issue of concern until recently as cities are getting more complex at a rate faster than we can develop theories for their understanding [8]. The current period might bring a tighter synchronization as it is largely admitted that: (1) cities can and should be interpreted as complex adaptive systems ([7,10]), (2) urban planning should evolve towards a more bottom-up and decentralized process ([15,33]) and (3) urban models may not be seen anymore as predictive black boxes but rather as mediating objects accompanying knowledge building and sharing in an ever changing complex environment ([7,29]).

Unsurprisingly, these three characteristics converge with the fundamental properties of agent-based modelling. In this context, several authors like Rasouli and Timmermans ([35], p. 19) call for a shift towards more integral microscopic models of choice behavior, allowing more integral policy performance assessments. Such an emphasis on desegregation is by no means a recent one; for example, Waddell [42] recalls that moving to disaggregated data and models was one of the main recommendations of the International Conference on Land Use Modeling hosted by TMIP in 1995. However, we partially diverge on the principle of integral microscopic models as, according to Couclelis [14] cited by Crooks, Castle and Batty ([16], p. 418), "a model has to be built at the right level of description for every phenomenon, using the right amount of detail for the model to serve its purpose". Fully desegregated modelling of urban systems comes at a cost that is not limited to computational burden, it also entails theoretical shortcomings as warned by Crooks, Castle and Batty ([16], p. 429): one major limitation of agent-based models [] is their arbitrariness due to the perceived need to represent the world in as rich a manner as possible. Henceforth, there exists a tension between the need to develop more sophisticated 'people-centric' models (e.g. models that are driven by social behaviour and interactions rather than those models driven by physicality such as land use and infrastructure demands) and the limitations associated with a pure reliance on individual-based paradigms. We will revisit this issue in the last section.

Importantly, modelling of complex urban systems does not necessarily involve developing complex models - a complex model being different from a model of a complex system. Following Axelrod [3], we argue that the complexity of a model - especially of agent-based ones - might reside in its simulation outputs, not in its hypotheses and structure. More to the point, Simon [37] emphasized how exploring a complex system can be done with simple models. In an urban modelling context, [21] concludes that unraveling complexity requires complex

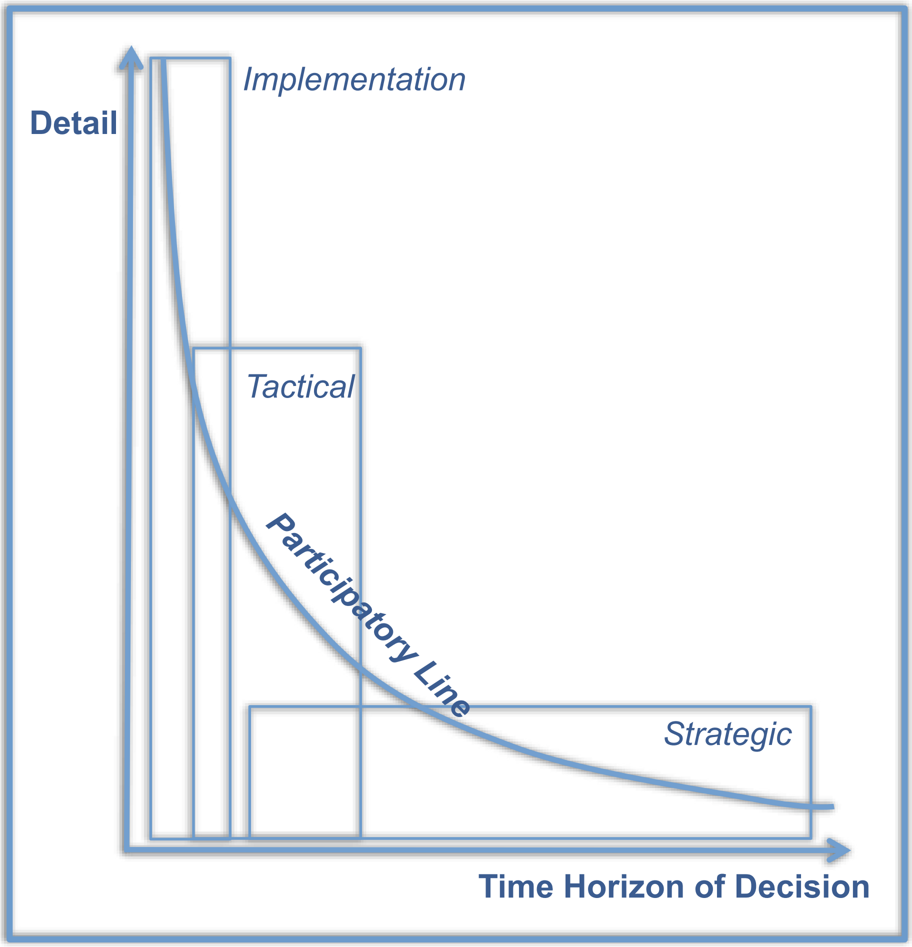

Fig. 2. Trade-offs among strategic, tactical and implementation planning and the necessity to include participation at every stage of the process (adapted from [26], p. 38)

and sophisticated analysis. If such analysis is supported by models, then the modeling system is bound to be complex (although it may be composed of simpler and more readily understandable sector components) ([21], p. 33).

Brömmelstroet and Pelzer [11] warn against the temptation of developing too complicated models as progress in computational power and availability of more data on higher levels of detail has allowed models to move into a higher level of detail, both in their structure (e.g., agent-based, CA) as well as in their geographical scale. Yet these models are much less operational for policy purposes than the previous generation of land-use-transport models, and are largely pedagogic in emphasis and often intent ([11], p. 383). This somehow counter-intuitive statement needs to be evaluated in the context of urban planning processes these models are supposed to serve. As emphasized by Lee [26], one cannot reduce urban planning to a single operation that would be defined by a specific temporal horizon and a specific level of details. Therefore, aiming for a universal urban model, working equally at strategic, tactical and implementation levels (Fig. 2) may be as vain as counter-productive. Moreover, the recognition that urban planning is first and foremost a political process has prompted planners in democratic societies to develop participatory approaches [15]. Engaging with relevant people at different levels of details and time horizons necessitates an ecosystem of fit-for-purpose models rather than a fit-for-all approach [29]. There is also a rise in scenario planning approaches which embrace multiple stakeholder engagement in the plan formulation process ([23,24,32]). Such data driven approaches are relevant to explore an envelope of planning scenarios, using GIS based planning support systems ([30,31]).

3 Key Challenges for Urban Modelling

Most challenges for urban modelling listed by Crooks, Castle and Batty [16] remain work-in-progress today. Beyond aforementioned concerns about model complexity and inherent limitations of individual-based paradigms, Wegener [44] - envisaging the growing challenges posed by energy scarcity, climate change and their associated social conflicts - identifies several limitations of existing urban mobility models: (1) relying too much on the extrapolation of past trends, (2) searching mainly for stable equilibrium, (3) focusing too much on observed behaviors and preferences, (4) prioritizing lengthy calibration and details. The author calls for a paradigm shift in urban modeling, based on four principles: (1) theory-based generative modelling rather than extrapolation, (2) constraint-led rather than preference-driven modelling, (3) plausibility analysis rather than predictive modelling and finally (4) back-casting rather than forecasting. These principles are directly inspired by Epstein's concept of generative social science that aims at testing social theories by growing artificial societies in agent-based models and confronting the outcomes with field evidence [18]. Due to the complexity of urban systems and the fragmented nature of evidence, the proposed paradigm shift can only operate in a multi-disciplinary environment which embraces a what if? exploratory scenario planning approach which is driven by the best available data, models combined with expert and citizen opinions.

These challenges can also be addressed according to core features of urban planning. Modern urban planning is characterized by (1) the complexity of urban processes and their responses to policies, (2) the multi-dimensional nature of urban planning's focus and outcomes, (3) the necessity to deliver plausible futures for cities and (4) the increasing demand for participative policy-making in democratic societies [16].

3.1 Addressing the Complexity of Urban Processes

Following Harris [21] and Crooks, Castle and Batty [16], we don't see any advantage in building massive and highly detailed agent-based models of urban systems for the only reason that modern computing allows it. Arbitrary heuristics and intractable feedback loops will always limit the analytical power of these cybernetic juggernauts. We suggest instead developing modular architectures that can host complementary modelling paradigms in different and fit-for-purpose modules. Each module would allow for proper and replicable theory testing and should reduce path dependencies and lock-in effects. For example, a well-designed modular architecture would allow for continuous traffic modelling [20] to co-exist with traffic micro-simulation [4] or agent-based transport demand modelling [22]. Although the need for hybrid traffic models has been long identified [12], there is still a need for operational models to be developed (see [39]). Hybridization can affect both lateral interactions between various classes of agents and hierarchically nested architectures. Melbourne-Thomas et al. [28] provide an example of a simulation model coupling within a cellular automaton a differential equation-based model of fish-coral-algae dynamics and an agent-based model of coastal development and fishing activities along the Yucatan peninsula (Mexico). This approach allowed for the integration and validation of phase transitions in the ecological model and for the creation of an empirical model of human activities based on historical records and social surveys. Pumain and Sanders [34] provide a comparison of various hierarchical architectures in the context of interconnected cities.

As long as the theoretical integrity and tractability of each module is preserved, these agent-based architectures can be massively distributed on high performance computing (HPC) clusters. Connectivity and interoperability between modules can efficiently be dealt with hierarchical formalisms like DEVS [45]. However, regardless of their architecture and constituting modules, validation of such modelling frameworks will always require mixed methods approaches, involving direct observations, model-to-model comparison and expert judgment [27].

3.2 Addressing the Multi-dimensional Nature of Urban Growth

As urban growth has long been recognised as a multi-dimensional process [15], these various dimensions apply not only to planning outcomes, but also to the processes influencing or being affected by policy decisions. While some integrated models already take into account some of these dimensions like land use, transport and residential mobility ([4,22]), none of them to date are able to preserve the integrity of embedded social entities. Ideally, these models should be able to link individual behaviours across various dimensions of urban life (switch on the light, turn on the tap, drive the car,) in order to take into account essential trade-offs and synergies.

Within a modular and incremental architecture ([13]), ontology-based synthetic populations could feed into various conceptual modules describing relevant urban components. At the implementation level shuttle models would encapsulate simplified or limited combinations of the modules in order to engage with specific stakeholders on a given set of issues. Following Perez ([29], p. 156), these shuttle models, to be consistent with the global conceptual model, would need to respect the integrity of a common ontological architecture. Each interactive model could use a subset of ontological components or simplified versions of some of them as long as their local solution space doesn't violate the boundaries of the overall solution space generated by the core model.

3.3 Addressing the Need to Deliver Plausible Futures for Urban Systems

Trend-based forecasting models aren't suitable for exploring the evolution of complex urban systems as they are characterised by (1) strong path dependency [2] and (2) endogenous and sometimes spontaneous changes [38]. Therefore data-driven extrapolations have to be replaced by theory-driven generative approaches [18], favouring back-casting reconstruction of past urban dynamics in order to validate endogenous assumptions and detect path dependencies before moving into forecasting mode [36]. In this context, data assimilation methods, guiding simulated urban forecasts, will play an increasingly important role [43]. The use of evolving synthetic populations rather than demographic trend-based projections is also becoming an alternative approach to develop more plausible futures [22]. Finally, when it comes to individual and collective behaviours, we need to move from traditional preference-based utility functions to alternative approaches focusing on response and adaptation to constraints in order to develop more robust and more plausible constraint-based scenarios [19].

3.4 Addressing the Need for Participation in Urban Planning

The political nature of urban planning has first forced authorities in democratic societies to communicate with communities through public consultations and exhibitions [15]. Then, some twenty years ago, they have taken advantage of advances in information technology to properly engage with communities through participation. Three approaches are particularly suited to coupling with urban modelling. First, Virtual Reality (VR) technology allows for 3D visualisation of actual and hypothetical urban spaces that can be assessed by various groups of stakeholders [40]. Participatory Planning Support Systems (PPSS), such as What if? can be used to discuss and select various planning scenarios ([24,30]). Finally, serious gaming and Role Playing Games (RPG) have proven highly successful in creating consensus around specific planning options in contexts like infrastructure renewal [17] or peri-urbanisation [9]. The development of these games can be easily associated with the concept of shuttle model proposed by Perez [29] whereby each game aims at exploring specific aspects or issues of a broader urban model with relevant participants in order to provide them with deeper insights and/or eliciting new knowledge to enrich or validate the core model.

4 Conclusions

Understanding the dynamic of urban systems, in an era of ever growing complexity, is more than ever of crucial importance. Increased collaborations between scientific research and urban planning are needed. Moreover, pushing towards more individual-based and people-centric approaches should not dismiss the importance of (1) multi-scale both spatial and temporal protocols, and (2) coupling whenever needed theories, concepts, formalisms and technologies. Urban modelling for urban planning needs to move away from massively distributed individual-based models in order to concentrate on more modular approaches mixing various modelling paradigms. The latter have proven their efficiency in testing theories dealing with the complexity of urban systems and the multi-dimensional nature of urban growth, in order to build and explore plausible trajectories of urban systems.

All the above cannot improve outcomes from urban planning without taking into account its political nature. In democratic societies, participation has become a vade mecum of urban planning. However, we argue that more needs to be done in order to involve stakeholders in the modelling process itself. Participatory modelling may therefore help bridging the gap between public expectations and policy makers.

This is an ambitious agenda that will need the multiplication of mediating forums between modellers and planners (such as the Centre for Urban Science and Progress in New York, the Advanced Urban Modelling Conference in Cambridge or the UrbanGrowth NSW University Roundtable in Australia). We hope that the Agent-Based Modelling for Urban Systems (ABMUS) community will become one of these international forums. Such a bottom up modelling approach lends itself to being incorporated in What if? scenario planning support system methodologies and offer great potential in assisting city planning endeavours as we plan for a global population fast approaching 10 billion.

References

1. Arbesman, S.: Overcomplicated: Technology at the Limits of Comprehension. Current, New-York (2016). 244 p
2. Arthur, B.: Urban systems and historical path dependence. In: Ausubel, J., Herman, R. (eds.) Cities and Their Vital Systems: Infrastructure Past, Present and Future, pp. 85–97. National Academy of Engineering, Washington DC (1988)
3. Axelrod, R.: The Complexity of Cooperation: Agent-Based Models of Competition and Collaboration. Princeton Studies in Complexity. Princeton University Press, NJ (1997). 232 p
4. Balmer, M., Axhausen, K., Nagel, K.: Agent-based demand-modeling framework for large-scale microsimulations. Transp. Res. Rec. J. Transp. Res. Board **1985**, 125–134 (2004)
5. Batty, M.: A chronicle of scientific planning: the Anglo-American modeling experience. J. Am. Plann. Assoc. **60**(1), 7–16 (1994)
6. Batty, M.: Fifty Years of urban modeling: macro-statics to micro-dynamics. In: Albeverio, S., Andrey, D., Giordano, P., Vancheri, A. (eds.) The Dynamics of Complex Urban Systems An Interdisciplinary Approach, pp. 1–20. Physica-Verlag, Heidelberg (2008)
7. Batty, M.: The New Science of Cities. MIT Press, US (2013)

8. Batty, M.: Can it happen again? planning support, Lee's requiem and the rise of the smart cities movement. Environ. Plann. B Plann. Des. **41**, 388–391 (2014)
9. Becu, N., Frascaria-Lacoste, N., Latune, J.: Experiential learning based on the newdistrict asymmetric simulation game: results of a dozen gameplay sessions. In: Hybrid Simulation and Gaming in the Networked Society: The 46th ISAGA Annual Conference 2015 (2016). www.hal-01253024
10. Bretagnolle, A., Daude, E., Pumain, D.: From theory to modelling: urban systems as complex systems. Cybergeo Eur. J. Geogr. (2006). http://cybergeo.revues.org/2420. Accessed 19 Sep 16
11. Brommelstroet, M., Pelzer, P.: Forty years after Lee's requiem: are we beyond the seven sins? Environ. Plann. B Plann. Des. **41**, 381–391 (2014)
12. Casas, J., Perarnau, J., Torday, A.: The need to combine different traffic modelling levels for effectively tackling large scale projects adding a hybrid meso/micro approach. Procedia Soc. Behav. Sci. **20**, 251–262 (2011)
13. Cottineau, C., Chapron, P., Reuillon, R.: Growing models from the bottom up. An evaluation-based incremental modelling method (EBIMM) applied to the simulation of systems of cities. J. Artif. Soc. Soc. Simul. **18**(4), 9 (2015)
14. Couclelis, H.: Modelling frameworks, paradigms, and approaches. In: Clarke, K.C., Parks, B.E., Crane, M.P. (eds.) Geographic Information Systems and Environmental Modelling. Prentice Hall, London (2002)
15. Couch, C.: Urban Planning: An Introduction. Palgrave Macmillan, London (2016). 344 p
16. Crooks, A., Castle, C., Batty, M.: Key challenges in agent-based modelling for geo-spatial simulation. Comput. Environ. Urban Syst. **32**(6), 417–430 (2008)
17. Dray, A., Perez, P., Jones, N., Le Page, C., D'Aquino, P., White, I., Auatabu, T.: The AtollGame experience: from knowledge engineering to a computer-assisted role playing game. J. Artif. Soc. Soc. Simul. **9**, 1 (2006)
18. Epstein, J.M.: Generative Social Science: Studies in Agent-Based Computational Modeling. Princeton University Press, Princeton (2007). 350 p
19. Fosset, P., Banos, A., Beck, E., Chardonnel, S., Lang, C., Marilleau, N., Thévenin, T.: Exploring intra-urban accessibility and impacts of pollution policies with an agent-based simulation platform: GaMiroD. Systems **4**, 5 (2016)
20. Geroliminis, N., Sun, J.: Properties of a well-defined macroscopic fundamental diagram for urban traffic. Transp. Res. Part B **45**, 605–617 (2011)
21. Harris, B.: The real issues concerning Lee's requiem. J. Am. Plann. Assoc. **60**(1), 31–34 (1994)
22. Huynh, N., Perez, P., Berryman, M., Barthelemy, J.: Simulating Transport and land use interdependencies for strategic urban planning - an agent based modelling approach. Systems **3**(4), 177–210 (2015)
23. Klosterman, R.E.: The what if? collaborative planning support system. Environ. Plann. B Plann. Des. **26**(3), 393–408 (1999)
24. Klosterman, R.E., Pettit, C.J.: An update on planning support systems. Environ. Plann. B Plann. Des. **32**(4), 477–484 (2005)
25. Lee Jr., D.B.: Requiem for large-scale models. J. Am. Inst. Plann. **39**(3), 163–178 (1973)
26. Lee Jr., D.B.: Retrospective on large-scale urban models. J. Am. Plann. Assoc. **60**(1), 35–40 (1994)
27. Macal, C.M., North, M.J.: Tutorial on agent-based modelling and simulation. J. Simul. **4**(3), 151–162 (2010)

28. Melbourne-Thomas, J., Johnson, C.R., Perez, P., Eustache, J., Fulton, E.A., Cleland, D.: Coupling biophysical and socioeconomic models for coral reef systems in Quintana Roo, Mexican Caribbean. Ecol. Soc. **16**(3), 23 (2011)
29. Perez, P.: Science to inform and Models to engage. In: Finnigan, J., Raupack, M. (eds.) Negotiating Our Future: Living scenarios for Australia to 2050, vol. 2, pp. 147–160. Australian Academy of Science, Canberra (2013)
30. Pettit, C.J., Klosterman, R.E., Delaney, P., Whitehead, A.L., Kujala, H., Bromage, A., NinoRuiz, M.: The online what if? planning support system: a land suitability application in Western Australia. Appl. Spat. Anal. Policy **8**(2), 93–112 (2015)
31. Pettit, C.: Use of a collaborative GIS-based planning support system to assist in formulating a sustainable development scenario for Hervey Bay, Australia. Environ. Plann. B Plann. Des. **32**(4), 523–545 (2005)
32. Pettit, C., Pullar, D.: A way forward for land use planning to achieve policy goals using spatial modeling scenarios. Environ. Plann. B Plann. Des. **31**, 213–233 (2004)
33. Pumain, D., Sanders, L., Bretagnolle, A., Glisse, B., Mathian, H.: The future of urban systems. In: Lane, D., Pumain, D., Van der Leeuw, S., West, G. (eds.) Complexity perspectives on innovation and social change ISCOM. Methods Series, pp. 331–359. Springer, Berlin (2009)
34. Pumain, D., Sanders, L.: Theoretical principles in interurban simulation models: a comparison. Environ. Plann. A **45**, 2243–2260 (2013)
35. Rasouli, S., Timmermans, H.: Uncertainty in predicted sequences of activity travel episodes: measurement and analysis. Transp. Res. Rec. J. Transp. Res. Board **2382**, 46–53 (2013)
36. Sanders, L., Pumain, D., Mathian, H., Guerin-Pace, F., Bura, S.: SIMPOP: a multi-agent system for the study of urbanism. Environ. Plann. B **24**, 287–305 (1997)
37. Simon, H.: The architecture of complexity. Proc. Am. Philos. Soc. **106**, 467–482 (1962)
38. Sole, R., Manrubia, S.C., Luque, B., Delgado, J., Bascompte, J.: Phase transitions and complex systems: simple, non-linear models capture complex systems at the edge of chaos. Complexity **1**(4), 13–25 (1996)
39. Taplin, J., Taylor, M., Biermann, S.: Transport Modelling Review: Independent Review. Planning and Transport Research Centre (PATREC), Curtin University, Perth (2014). 124 p
40. Trubka, R., Glackin, S., Lade, O., Pettit, C.J.: A web-based 3D visualisation and assessment system for urban precinct scenario modelling. ISPRS J. Photogrammetry Remote Sens. **117**, 175–186 (2016)
41. United Nations. Population Division. World Population Prospects: The 2015 Revision: Highlights. UN (2015)
42. Waddell, P.: UrbanSim: modeling urban development for land use, transportation, and environmental planning. J. Am. Plann. Assoc. **68**(3), 297–314 (2002)
43. Ward, J.A., Evans, A.J., Malleson, N.S.: Dynamic calibration of agent based models using data assimilation. R. Soc. Open Sci. **3**(4), 150703 (2014)
44. Wegener, M.: The future of mobility in cities: challenges for urban modelling. Transp. Policy **29**, 275–282 (2013)
45. Zeigler, B.P.: Discrete event system specification framework for self-improving healthcare service systems. IEEE Syst. J. **99**, 1–12 (2016)