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Complexity Science: The Urban is a Complex Adaptive System

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1. Introduction

Complex systems are a transdisciplinary area of research and complexity theory cannot be narrowed down to a singular definition. It - also referred to as the complexity sciences - has emerged through independent and overlapping influences of multiple disciplinary explorations into systems theories over time. Concepts from physics, economics, biology, sociology and computer science have impacted on and been shaped by complex systems as an evolving body of knowledge aimed at understanding real world phenomena characterised by temporal change, unpredictability and particularly in the case of biology, ecology or sociology, evolution. Urban phenomena studied through the lens of complex systems are typically temporal, dynamic, relational and non-linear. Complex systems provide a field of inquiry rather than just a collection of specific disciplinary approaches (Laszlo and Krippner 1998).

This chapter explores the emergent field of urban complexity and demonstrates how a distinct and yet transdisciplinary collection of theories have resulted in a growing research area examining the urban as temporal processes of change with possibilities for self-organisation, unpredictability and human intervention. Section 2 provides an overview of urban complexity and its distinct conceptual framework. Section 3 provides a historical perspective on the development of complexity theory and summarises significant influences. Section 4 examines historical attempts to create a science of cities as systems. Section 5 posits that the urban as a process is more compatible with temporal, dynamic and relational complexity concepts than historical definitions of cities, and summarises the key concepts and phenomena in urban complexity research. Section 6 lists pioneers of urban complexity and locates contemporary concerns and theorists. Section 7 describes the importance of computer modelling and simulation to urban complexity research, while introducing the basic computational models used for simulation. Section 8 demonstrates the potential limitations to a modelling based complexity approach. Section 9 examines the advent of Big Data and the Internet of Things as a disrupter to current research methods, examines key research areas and suggests avenues for transdisciplinary overlaps. Section 10 concludes with a summary of the main concepts in the field of urban complexity and the opportunities for research looking ahead.

2. Urban Complexity

There has been an observable shift away from primarily location and equilibrium based theories for cities, to the recognition of the urban process as a combination of relational flows. The seemingly chaotic or non-linear urban phenomena resulting from the combination of hard and soft systems (Checkland 1989) or physical and environmental aspects of the urban with human interaction, motivation, perception and creation are particularly suited for study using a complex systems framework. Examples include socio-spatial and morphological change, evolutionary social networks, environmental modulation and emergence of economic and political structures. Within the complexity sciences, it is possible to see a clear shift from an initial focus on observable and quantifiable physical phenomena to a recent human centric approach resulting from engagement with social and ecological complexity.

Within urban processes, focus on component/element/agent interactions at high levels of granularity, allowing observation of emergent patterns at other spatial and temporal scales of behaviour aims to unravel the logic of urban patterns and flows, not understandable through reductive approaches. Recognition of all non-engineered systems in the real world as ‘open systems’ (Von Bertalanffy 1950) obviates acknowledgement of interactions between multiple systems and system environments (understood as the wider context of a defined system). This makes it impossible to undertake isolated laboratory studies based on reductive scientific approaches, resulting in the development of a specific area of urban research based on data from real world phenomena. Human perception, motivation and action, within processes of urban change result in complex phenomena. Urban complexity research focuses on patterns, trends and change within an open-ended continuum and evolving future outcomes.

3. The Development of Complexity Theories

Influential historical, theoretical and experimental advancements, along with shared transdisciplinary concepts contributing to the development of complex systems as an emergent field, are summarised below. These provide a context to the most prevalent approaches used to study and model urban phenomena from a complex systems perspective.

3.1. Systems Theory

Alexander Bogdanov used the term ‘tektology’ as early as 1912-17, to refer to an approach unifying disciplines by understanding phenomena in terms of systems of relationships and organisational principles. However, it was Ludwig Von Bertalanffy who popularised the modern term, with his advance of general system theory (GST) (Von Bertalanffy 1950). Bertalanffy already differentiated between ‘closed systems’ typical of mechanistic systems and ‘open systems’ for living systems. He suggested that the laws of thermodynamics did not always apply to the latter. Talcott Parson’s action theory, Alfred North

Whitehead’s view of the world as a network of interrelated processes, and Niklas Luhmann’s social systems theory, are also notable contributions to systems theory.

Systems theory is multi-disciplinary and in part developed to allow trans-disciplinary comparison. A system in the loosest sense refers to identifiable organisations of phenomena. System definitions can be independent of substance, spatial or temporal scale of existence. However, the definition of sub-systems, components and hierarchies, are critical to a system definition. Models of systems can be used to investigate both the topological structure and the interactions between entities or components of the collective defined as a system. Complexity suggests that a component of a system can only be understood in the context of relationships with other components (Ackoff 1981), and open systems – those that exchange energy or information with their environment - can only be understood in the context of other related systems (Nicolis and Prigogine 1977). An important aspect of systems theory in the context of the urban research is that it contrasts with scientific reductionism and suggests a holistic consideration is essential.

3.2. Dynamical Systems

Dynamical systems contributes the ideas of dynamics and temporal change to systems research. These two aspects were integral in the development of research on long-term system behaviour for mechanical or deterministic systems. Mathematical models predict systemic change in time or dimension. The classic example refers to predictability of the position of a pendulum clock in time. However, dynamical systems have utilised to research natural phenomena such as the changing populations of fish in a lake over seasons. Much of contemporary dynamical systems research focuses on chaotic systems. Historically, this approach was used to study weather, the movement of the solar system, and growth of crystals.

3.3. Chaos Theory

Chaos theory contributes the idea of unpredictability to complex systems. This is a formative theory questioning the belief that science can predict reality, as previously conceived in a mechanical Newtonian universe. In a failed attempt to solve King Oscar II of Norway and Sweden's mathematical challenge in 1889, Henri Poincaré experimented with the three-body-system. His experiment aimed to determine the motions of the three bodies over time based on knowledge of the initial masses, positions and velocities. Instead of finding a solution, Poincaré found that the tiniest differences in initial conditions could result in dramatically different outcomes, not related in magnitude to the changes in initial conditions. This idea of an unpredictable universe was popularised as the 'butterfly effect' by Edward Norton Lorenz. In the 1950's and 60's Lorenz reran a partially completed sequence on a computer model used to predict weather using data noted from the end of the previously incomplete sequence. His use of numbers rounded by a decimal point resulted in highly unexpected results. Further experimentation led Lorenz to conclude that the precision required to repeat predictable outcomes in such dynamic systems was possibly beyond the realms of human accuracy, resulting in the suggestion that long-term prediction is in fact impossible (Lorenz 1963). When explaining the concept at the 1972 meeting of the American Association for the Advancement of Science in Washington, Lorenz asked whether the flapping of a butterfly in Brazil could potentially result in a tornado in Texas, thus popularising the phrase. Chaotic systems are unpredictable and yet theoretically deterministic in that the initial conditions determine future behaviour. Hence they are typically differentiated from complex systems.

3.4. Cybernetics

Cybernetics contributes the concept of circular causality to complex systems. The word 'cybernetique' was first used in 1834 - by the French physicist and mathematician André-Marie Ampère - in reference to civil government. However, Norbert Wiener popularised the term in its contemporary sense in his book ‘Cybernetics: or control and communication in the animal and the machine’ (Wiener 1948). Cybernetics at a basic level is a field concerned with theories of communication and control. This has been of particular significance in the context of automatic control systems or self-correcting systems. However, multiple definitions exist due to the multi-disciplinary appeal of cybernetics. Gordon Pask, from his educational theory background was interested in cybernetics as the art of manipulating defensible metaphors (Pask 1961). Warren McCulloch, from a philosophy background, was interested in the communication between observer and environment (McCulloch 1965). Gregory Bateson, as an anthropologist was focused on form and pattern (Bateson 1970). Stafford Beer, from his management perspective was interested in effective organisations (Beer 1966). The multiple aspects of research under a cybernetics umbrella do have a common underlying framework. Most cybernetic processes are concerned with how systems react to information and how this leads to additional actions or change to the system itself. The idea is to improve either one or both of these in subsequent iterations. Examples of systems displaying cybernetic properties can be biological, cognitive, mechanical, social, etc. The nervous system is a biological example, while the autopilot system in an aeroplane is a mechanical example. Cybernetics in practice is often aimed at improving efficiency and works on the basis of identified performative goals. Circular causality contributes to regulation and control within a technological context.

Cybernetics is related to models, theories and phenomena in complex systems. Common areas include cellular automata, game theory and artificial intelligence. The last emerged from cybernetics and became distinct field of research.

4. Development of a Systems Approach for ‘Cities’

A systems approach to cities emerged in the 1950’s and 1960’s in parallel with the development of general systems theory and cybernetics. Before the development and application of complex systems based approaches, there were multiple attempts to control and manage the growth of cities using scientific methods and principles. The coming of the industrial city and related conditions exacerbated the desire to control growth and plan cities scientifically from the top-down. Theories and models of cities developed hand-in-hand as the idea of centralised planning and scientific analysis became popular. Ultimately this movement was unable to provide the general approach to planning cities it aimed for and was set to fail from its very inception due to a number of theoretical concepts borrowed from other disciplines and applied erroneously to cities. The developments during this time do provide the base from which a complexity theory of the urban is developing. This section provides a short introduction to the development of a 'science of cities' (Batty 2013b), the adaptation of systems theory and the main shortcomings of the approach.

An early scientific approach to city planning in Europe can be traced back to Cerdá, a Catalan Spanish urban planner who designed Eixample in Barcelona and coined the term urbanism ('urbanización' in spanish). As an antecedent to the development in the 1950's, Cerdá pioneered a form of city planning based on analysis of needs and categorisation of what he termed the five bases of urbanisation in 1859. Namely the technical, administrative, legal, economic and political bases (y Puig 1999).

A precursor to a systemic bottom-up urban perspective comes from economics via Adam Smith in his book The Wealth of Nations (1776). In this book the concept of the 'invisible hand' is discussed in the context of a society in continuous competition based on diverse market forces. Intrinsic to this idea of a system, Smith also introduced the concept of a 'natural' level brought about by the competitive markets, or an optimised equilibrium. This concept was embraced both in economics (Orrell 2010) and in theories of cities, based on a predominantly mechanistic view of cities as systems in equilibrium or moving towards such a state.

Johann Heinrich Von Thünen, also an economist, spatialized the idea of bottom-up competition when he pre-empted location theory (Alonso 1964) by more than a hundred years. In his consideration of marketplace, transport and agricultural patterns, for his Isolated State (Der Isolierte Staat) in 1826, Thünen incorporated space into previously 'spaceless' economic models. Location theory revolutionised urbanism as settlement geographers with economic considerations and physical analogies utilised it to explain settlement patterns (Portugali 2011a).

Following Thünen's work, Alfred Weber in his Theory of the Location of Industries (1929) explored spatial agglomeration while developing his location triangle to optimise industrial locations based on proximity to others, labour and transport costs (Portugali 2011a). Central place theory developed independently by Christaller (1933/1966) further strengthened location theory by describing how commercial centres and primary resources could be used to locate industry in an ordered hierarchy (Batty 2007).

From the 1950's there was an attempt to spatialize economic, political and social processes, resulted in the quantitative turn in geography. The quantitative turn focused on an attempt to transform previous descriptive studies of cities into an analytical science (Burton 1963). Town planning (urban planning), predicated itself on the formation of top-down controls, idealised city visions and masterplans, in an effort to provide citizens with healthier cities. Within mainstream urban planning and city sciences, the possibilities of bottom-up phenomena were acknowledged as threats in an industrial society displaying signs of uncontrolled growth based on private interests. This in combination with a concern for chaotic uncontrolled cities without appropriate spatial or social order led to the idea that cities should be manufactured and managed (Batty and Marshall 2012).

Patrick Geddes – the father of British town planning - who originally trained as a biologist, can be seen as an early appreciator of the organic complexity of cities (Batty and

Marshall 2009). However, in practice his attempts to incorporate this aspect were hindered by the adoption of a top-down approach and the belief in a systemic equilibrium for cities. Patrick Abercrombie the creator of the Greater London Plan (1944) and author of 'Town and Country Planning' (1933) was clearly espoused that planning was a necessity and reliance upon 'evolutionary chaos' related to Adam Smith's ideas was not (Abercrombie 1937). Designing an organic city provided no direct approaches in comparison with the easily applied concept of the city as a machine (Marshall 2009).

Given the diverse origins and sometimes conflicting approaches involved in the study of cities, the search for clear strategic approach or a common framework is unsurprising. General systems theory developed by Ludwig von Bertalanffy (1968), with its origins in biology, suggested that different material systems may have a common generic structure (Von Bertalanffy 1968). With the previously established understanding of bottom-up systems strengthening the possibility of different disciplines working on related aspects of the city, a general systems approach was also adopted by the social and professional sciences such as sociology and city planning. As architectural determinism and social administration were abandoned for a more systematic social science approach, a systems approach to cities bloomed briefly in the 1960's (Chadwick and Francisco 1971).

A parallel theoretical advancement in engineering related to control systems continued to influence systems thinking in cities. A cybernetic approach to the city was embraced, and with it the idea of top-down controls and equilibrium or steady state systems (Wiener 1965). Mechanical systems also provided the basis for the treatment of various city systems as non-evolutionary closed systems, controlled through negative feedback. A number of disciplines embraced a systems approach, as demonstrated by David Easton's book 'A Systems Analysis of Political Life' (1965), Daniel Katz and Robert Kahn's book 'The Social Psychology of Organisations' (1966), and Karl Deutsch's book 'The Nerves of Government' (1963) (Batty and Marshall 2012). The combination of a positivist approach based on philanthropic origins combined with the bias towards equilibrium based models and theories borrowed from engineering and economics proved inadequate to the task of understanding cities as evolving open systems. In 1973, David Harvey provided a comprehensive critique of the existing quantitative-positivist culture in urban studies and joined a number of leading urbanists who questioned the scientific and social validity of their own project. McLoughlin's book 'Control and Urban Planning' (1973), was criticised by many practitioners as an exercise in scientism and technocracy (Portugali 2011b).

The development of a systems approach for cities resulted in short-lived practical application, but provided the basis for the emergence of a more sophisticated understanding based on a complex systems framework over the following decades.

5. Complexity and the Urban Process

It is possible to identify a gradual distinction between the definition of cities and the urban by tracing attempts from multiple disciplinary perspectives, since the advent of modern urban planning. Such an exercise spans from Mumford in the early 20th century to Batty in early 21st, demonstrating the need to find alternatives to definitions based primarily on relative location and cybernetics. These serve an important step in the shift away from Thünen and Alfonso's work and the development of a complexity perspective related to the urban as a process involving social and political patterns and flows.

Historic definitions of cities ranged between self-imposed or local designations based on defensive, historic, natural, legal or administrative boundaries. Despite the changing and sometimes contested nature of city boundaries, spatiality and location played significant roles. At the beginning of the 20th century, spatial definitions began to incorporate reference to agglomerated human activity and density. Mumford provided us with one of the one of the earliest definitions of cities as agglomerations by describing them as points of concentration of power and culture of a community (Mumford 1938). The increasing emphasis on human activity can also be seen in Giedion Sjoberg's attempt to distinguish between agricultural areas and cities by reference to size, occupation and literacy (Sjoberg 1965). Arnold Toynbee described cities based on functional differences between a dense developed cluster with a specialised population supplying goods and services to the country in order to acquire food (Toynbee 1970). Max Weber's definitions of cities were based on the existence of evidence of fortification, a market, a court and some degree of political autonomy (Weber, Martindale, and Neuwirth 1958). While these attempts demonstrate the incorporation of human activity into the definition of cities, they also support an underlying assumption that cities are in fact physical locations at or away from which activities occur.

In comparison with the locational bias of city definitions, the urban is often defined as a process (Pahl 1966, Harvey 1978, Castells and Sheridan 1977). The emphasis on 'relationism' rather than 'relativism' differentiates most complexity theory considerations of the urban process from a Marxist-poststructuralist perspective (De Roo, Hillier, and Van Wezemael 2012). The shift to the idea of a process or continuum from a location or artefact is evidenced in multiple disciplinary areas, from sociology to architecture. In his book 'The City Assembled, The Elements of Urban Form Through History', despite still using the word 'city' Kostof refers to both process and flow (Kostof 1992). From a complex systems perspective a process is a useful categorisation due to the intrinsic association with time, relational dynamics and change.

The urban as a process provides multiple possibilities for concept transfer and theoretical cognition from a complex systems perspective. Dynamics and temporal change are essential qualities in the study of urban systems and dynamical systems provide a useful theoretical basis to understand structural change. The relational aspect of systems theory is important to the understanding of multi-dimensional processes of natural, engineered and social change. These concepts from systems theory - sometimes incorporated within the older definitions of cities -

are however not adequate for the description of a large number of observable urban phenomena. The urban displays aspects of social change, disorder and non-linearity (small actions leading to changes or unrelated magnitude), which are characteristic of open systems exchanging energy, matter and information with their environment or other systems (Prigogine 1984). Prigogine and Stengers work on open systems, and the spontaneous formation of spatial structures is important not only because of the formal similarities with urban spatial processes, but also because open systems are associated with biological and social systems rather than mechanical systems related to Newtonian models emphasising order and equilibrium. An open systems conceptualisation of the urban process resonates with the influence of human factors and multiple motivations in combination with external dynamics ranging from energy and material flows to economic exchange. Urban systems display phenomenon which are characteristic of systems that are far-from-equilibrium, where high levels of order can be observed, but these exist on the ‘edge of chaos’ (Batty 2007) maintained temporarily through external flows. Concepts from complexity such as non-linearity, self-organisation, emergence, adaptive and evolutionary systems provide additional theoretical frameworks capable of describing phenomena in the urban process.

5.1. Nonlinearity

Nonlinearity adds to the understanding of unpredictability already summarised in chaotic systems. The principles refer to the unpredictability of outputs based on known magnitudes of inputs. The majority of real world systems appear to be nonlinear, displaying qualities of positive and negative feedback and interference. Various disciplines use a nonlinear systems approach, such as nonlinear regression in statistics, nonlinear optics in physics and nonlinear population studies in ecology. The urban incorporates multiple interrelated nonlinear systems such as housing development, population epidemiologies and employment markets. Urban planning and policy has become an area of nonlinear research as interventions within the urban process do not always lead to intended outcomes.

5.2. Emergence

Emergence is a process in which smaller entities, components and patterns in a system interact with each other, resulting in the formation of larger (typically) entities or behaviours not observable at the initial scale. Within urban phenomena this is observable in bottom-up initiatives leading the development of wider policy, traffic jams resulting from the incremental actions of multiple drivers or the transformation of urban enclaves from one identifiable function to another e.g. a shopping area to an office area. In open systems, the interaction also encompasses the environment or other systems. This process is often irreducible. Jeffrey Goldstein an economist, suggests emergence is the formation of novel and coherent structures and patterns during self-organisation (Goldstein 1999). As identification of structure and pattern can be subjective depending on system definition and scale emergence is not purely objective in character.

Emergence is related to synergetics. This is Hermann Haken's exploration of small-scale interactions resulting in self-organising structures in open systems (Haken 1977). The theory of evolution is a potential example of emergence. George Henry Lewes, provided and early distinction between 'resultants' and 'emergents'. Where, resultants were phenomena that could be predicted by the preceding conditions . Emergents on the other hand, as seen in evolution demonstrated the possibility of completely new forms while still being related to previous stages (Lewes 1875).

There is tendency to assume that emergence occurs in systems without any top-down control. However, degrees of organisation, differentiation and connectivity appear to be requirements for occurrence. 'Noise' from interactions not effecting behaviour at other scales is distinct from emergence. An important quality of emergent systems is that they are open systems interacting with their environment. The phenomena exists in urban systems and natural systems, and is observable in both unplanned urban development resulting in recognisable patterns of utility and flocks of flying geese in constantly adjusted formation.

5.3. *Self-organisation*

Self-organisation is related to emergence but a distinction is possible. Conceptually emergent behaviour is identifiable at different scales from underlying actions while self-organisation occurs over time within the same scale space. Self-organisation is a process by which potentially random structures and patterns can be seen to form temporally in multi-entity systems. The significance of this for urban complexity is the lack of any observable or intentional top-down control (Sengupta 2011). Self-organisation can be observed in phenomena such as swarming in biological systems, stock market crashes in economic systems or unplanned human settlements. Fluctuations within a system, are amplified or dampened by positive or negative feedback loops and external influences.

5.4. *Complex Adaptive Systems (CAS)*

CAS are a particular category of complex systems incorporating additional phenomena of particular importance in real world systems. They exhibit the ability to learn from information collected through experience. John H. Holland suggested that complex adaptive systems not only have the ability to learn and adapt to repeating situations, but can also demonstrate anticipation in the process of adapting to expected future conditions (Holland 1992). Many ecologies and human social endeavours, including stock markets, political parties or communities, and online social networks can be studied using a CAS framework. The urban with its transitory goals, multiple actors, actions and motivations, is a process of transformation predicated on learning from experience and acting in anticipation. It is the possibly the ultimate complex adaptive system.

5.5. Resilience

Resilience has become an increasingly important concept in urban studies, planning and management. A clear distinction exists between engineering resilience and ecological resilience. The former is more useful for the consideration of manmade or engineered systems in need of maintenance and repair, with the degree of resilience related to robustness against external shocks. Ecological resilience embraces the possibilities of transformation and phase shifts into new states (Holling 1973, 1996). Gunderson and Holling expand further on the possibilities of evolving hierarchical systems demonstrating continual adaptive cycles while retaining the possibility of transformation into new systems in their co-option of 'panarchy' (Gunderson and Holling 2002). Urban systems such as railway infrastructure with slow rates of change can be researched using engineering resilience in the short-term, while open socio-ecological systems such as service provision or moving communities fall into ecological resilience frameworks.

5.6. Evolutionary Theory and Evolutionary Systems

CAS, resilience and emergence are related to evolutionary theories. From an ecological perspective the behaviour and the very structure of an ecosystem are emergent, based on species and environmental interactions (Mitchell and Newman 2002). Evolutionary systems in the context of the urban typically refer to societal evolution (Banathy 1998) rather than exclusively biological evolution. Evolutionary systems is an area of complex systems and not only a reference to Darwinian thought. It embraces concepts of self-organisation and co-evolution. Batty and Marshall suggest a need to understand the evolutionary nature of urban change (Batty 2013b, Marshall 2009) and the impossibility of completely planned urban futures, before attempting to intervene in the urban process.

6. Early and Contemporary Urban Complexity Thinkers

While mainstream urban theorists were attempting to control cities using top-down mechanistic, cybernetic or equilibrium based approaches, Batty reminds us that a few early luminaries did articulate perspectives that were strongly related to an understanding based on complex systems (Batty 2005, 2013b). Jane Jacobs, with reference to Weavers address to the Rockefeller Foundation in 1948, referred to cities as problems in organised complexity, which needed to be considered as an organic whole (Jacobs 1961). Popper acknowledged that futures were in fact unpredictable (Popper 1959). Berry attempted to demonstrate that cities were more like organisms than like machines in terms of being open systems related to other open systems (Berry 1964). Christopher Alexander suggested that cities were made of overlapping relational and multi-scale elements in his famous paper 'A City is not a Tree' by using the example of an abstract semi-lattice (multi-layered) structure rather than a branched tree-like structure to conceptualise the nature of cities (Alexander 1964). He was referring to the complex phenomena observable in contemporary studies of complex social networks. The fact that Alexander was ignored by the majority of urbanists did not stop his work on patterns (Alexander, Ishikawa, and Silverstein 1977) being embraced by computer programmers who developed a whole vocabulary of patterns within object orientated computer languages.

More recently a select number of complexity researchers have embraced urban complexity research and a contemporary field of study has emerged. Peter Allen explored underlying complexity and spatial evolution in his seminal book 'Cities and regions as self-organizing systems: models of complexity' (Allen 1997). Bettencourt and West continue to explore scaling laws in cities and nature, in an effort to demonstrate a quantitative theory of urban organization and sustainable development (Bettencourt et al. 2007). Portugali with his ongoing research into the state of urban complexity theory relatively recently introduced the importance of considering cognitive aspects of urban systems and the link to complex adaptive systems (Portugali 2004). Michael Batty has researched multiple aspects of urban complexity, including growth and scaling laws, and has recently worked on urban network and flows in parallel with Big Data analysis (Batty 2013a). All these approaches emphasise research into different aspects of urban complexity but stem from a common understanding of complexity based on change, unpredictability, self-organisation, emergence and evolution.

7. Computer Modelling and Simulation

The complexity sciences were instrumental in clarifying the limitations of Newtonian science or mechanistic science in explaining real world phenomena. The reliance on a Newtonian worldview proved incapable of incorporating human behaviour, societal norms, adaptive abilities and evolutionary processes. The traditional scientific process of analysis using reduction and subdivision until a system is broken down to the smallest possible components for study has proved inadequate for observation and explanation of higher-level patterns of behaviour or whole system behaviour. A commonly used quote appropriated by the complexity sciences from Aristotle is, "The whole is more than the sum of its parts".

Complexity can be observed in physical as well as biological systems. The urban process demonstrates a plethora of interrelated phenomena due to the combination of hard and soft systems (Checkland 1989). As a result, computer modelling and simulation has been adopted for study of the urban, with an increasing emphasis on the latter to enable study of the behaviour within or of a system. Methodologically this prioritises the study of dynamics between components, elements or actors over the specific descriptions of these, and aims to work with patterns created by smaller scale interactions. Due to the essential need for clear model descriptions, spatial scales and hierarchy have become common aspects of urban modelling. These are related to the older science of cities, but also to the need for multiple views of a system (E.g. local motivations and spatial development for the same system) (Allen 1997).

The complexity sciences are engaged in research of multiple aspects of the urban. While the approaches are diverse, the necessity of acknowledging complex phenomena within urban processes has led to a diverse range of computational modelling methods capable of simulating dynamics and change. These should be differentiated from purely analytic or mathematical models which are typically used for linear systems. There are however several obvious limitations to this method being applied to urban processes. It is not possible to identify, calibrate and simulate every component or dynamic resulting in real world phenomena, hence complex simulations are simplifications of the real world with sufficient behavioural qualities to test specific hypothesis. It is also an abstraction to remove an identified system from its environmental influences to consider it in isolation. Complexity from an ecological perspective advocates that the boundaries of urban systems are not in fact fixed and interactions between systems and environments and systems and other systems are essential to the understanding of change. Examples of computational simulations include modelling of large socio-dynamic networks, microsimulations of traffic and pedestrian flows, resource and energy flows, urban development, socio-spatial segregation and epidemiologies, and ecosystem simulations. While all different, the majority of these models are sophisticated versions of a number of limited model types, namely agent based models (ABM), cellular automaton (CA) and network models.

7.1. Agent based modelling

Agent based models (ABM) are computational models used to simulate and study behaviour of components or agents with intrinsic behaviours and the results of these interactions on the overall system of at a higher level where patterns become apparent. Agents can be individual or collective entities and typically interact with each other and an environmental field. The basic premise is that simple behavioural rules result in complex patterns of behaviour. Agent based models are widely used in the social sciences and can incorporate aspects of artificial intelligence and emergent behaviour.

7.2. Cellular automaton

Cellular Automaton (CA) are computational models (although there are analogue examples) made up of defined grid of cells, where the each cell is typically capable of reacting locally to its immediate local neighbouring cells. Sets of rules which can include probability and randomness influence the state of each cell as the model goes through changes based on time steps. Strictly speaking CA's are a form of agent based simulation, but the fixed grid or lattice lends itself to different experiments than a lattice free agent based simulation, where the agents typically move rather than changing state in a fixed location. The inherent spatial aspect of CA's has made it popular in urban simulations, especially at larger scales such as land use change. The classic example of a CA used to demonstrate an ever changing field is Conway'

7.3. Networks

Network models are graph networks where nodes and edges are used to define components/agents and relationships within a system. Complex networks tend to use this method to model real world systems such as technological networks or social networks. Dynamic network analysis (DNA) is a field where statistical network analysis and simulation is being brought together. Network simulations allowing the study of changes in network topology, dynamics and flows over time, and have started to incorporate the ability to learn and adapt. Network modelling has been used for urban infrastructure analysis for some time, but the growth of soft systems science and the discourse on emergent properties, ecological resilience and CAS has placed an emphasis on simulation and evolution.

8. Operational Limitations

The operational translation of complexity theory for studying real world urban phenomena is strongly related to the limitations of model development and system definition. The irreducibility of complex phenomena has meant that modelling and simulation has provided methods to engage with the study of behaviour in real world systems. However, all models and simulations are simplifications of reality allowing only selected criteria and available data to be modelled in order to test specific hypothesis. Collection of precise longitudinal data to model potentially unknown elements of urban systems is logistically difficult. The definition of a system for the development of a model also necessitates the definition of a closed or at least bounded system with limited or identifiable components, relationships and exchanges with the system environment. As real world systems, especially those related to human behaviour, are open systems, the complexity approach to the urban is limited by the sophistication of the models it relies on.

Complexity theory applied to the urban does not work towards specific aims like cybernetics. While this allows for unbiased research into real world phenomena, it is sometimes critiqued for its lack of socio-political agenda and focus in terms of desired urban outcomes in unpredictable situations. Working with uncertainty is not new in an urban systems context. Horst Rittel (Rittel 1972) along with Webber and Churchman introduced the concept of 'wicked' problems. The concept proposed that 'wicked problems' unlike clearly definable problems have no identifiable start, end or ultimate solution due to their intrinsic uncertain, non-linear and complex nature. Concepts related to 'wicked' problems after initial disregard are being increasingly recognised as an appropriate conceptual framework to engage with many urban processes. As uncertainties tend to be viewed as risks in urban policy and planned interventions, the typical approach is to reduce or avoid them as much as possible (Abbott 2009, Gunn and Hillier 2014). Operational engagement with the urban is typified by the need to research specific 'problems' toward 'specific' end outcomes, ignoring the theoretical importance of engaging with uncertainty, emergence and open ended possibilities to integrate unknown unknowns.

The locational and spatially biased definitions of cities are operationally clearer for modelling definition bounded systems than the transcalar processes of the urban. However, every city is in fact 'systems of systems of systems' (Johnson 2012) with reference to multi-level dynamics between subsystems. With the popularity of Smart City initiatives and discussions about holistic views of cities as well as better management of city systems enabled by new IT technologies, the systems of systems (SoS) label has grown in popularity. It was used by Samuel J. Palmisano the former chief executive of IBM to describe cities while incorporating references to complexity. Despite SoS definitions raise useful issues about the autonomy or absorption of systems and components (Boardman and Sauser 2006), as yet the this remains an engineering related definition. A complex systems theory of the urban would incorporate not only cities but systems of cities (Berry 1964). From a theoretical perspective, complex systems emphasises the need to engage with and accept ended processes incorporating uncertainty. As yet an operational perspective attempts to control these uncertainties instead of seeing them as opportunities.

9. Disruptions & Interdisciplinary Potential: Big Data & IoT

The advent of Big Data and the Internet of Things (IoT) has disrupted the complexity theory landscape and this is especially true within urban research, where reams of new data have become available without methodological precedents on how this information can be analysed or made useful. A fundamental shift away from isolated conceptual models and simulations with a fixed hypothesis, relying on previously observed or collected information is taking place. An increasing amount of digital data becoming available and much of it as real-time or near real time data has led to an increasing interest in data mining and analysis with the aim of seeing what patterns can be identified.

9.1. Big Data

The term Big Data was used in the context of ICT related data growth and new types of data in a number of presentations by John Mashey in the 1990's. At the time he was the chief scientist at Silicon Graphics in California (Lohr 2013). This term was elaborated on by Douglas Laney a data analyst from Gartner using the 'three V's' (namely data volume, data velocity and data variety) (Laney 2001). The initial definitions have expanded further, resulting in a lack of universally accepted definition. For the purposes of this article, Big Data refers to extremely high volumes of both structured and unstructured data that is difficult to process using traditional database or software techniques. Data types vary from corporate data to geo-located social media and live infrastructure updates. The nature of this data is that it is loosely structured and often incomplete or inaccessible.

9.2. The Internet of Things (IoT)

In 2008 the internet of people was overtaken by the Internet of Things (IoT) (Ashton 2009, Evans 2011). The term 'the Internet of Things' is credited to Kevin Ashton, cofounder and executive director of the Auto-ID Center at MIT. He described the shift from an Internet predominantly dependent on people to input data to one where computers took on this role and exchanged information on their own. The increasing number of IoT objects 'talking' to each other and to people over the Internet has resulted in an increase in the availability of recorded longitudinal data. New methods for analysis and filtration have become necessary as the increase of data from the growth of IoT leads to increasing complexity and large volumes of 'chatter'.

9.3. Data Mining & Machine Learning

Data mining is the process of analysing data in order to create comprehensible information structures or discover patterns. In order to deal with new types of information and patterns, data mining applications increasingly rely on machine learning and its supervised and unsupervised learning methods. Machine Learning is a branch of Artificial Intelligence (AI) (McCarthy et al., n.d.) researching systems that learn from data. This area of research has seen rapid expansion due to the inherent difficulties of making sense of Big Data using existing analytical methods. It is a process in which algorithms are used to identify how to perform tasks by comparing unknown examples against predefined examples (supervised learning). It also involves auto-categorisation of patterns using clustering logic (unsupervised learning) and systems that become more intelligent through greater exposure. The current Smart City trend towards optimisation of engineering urban systems using feedback loops and sensors, such as energy grids or transport, relate to the former method. The second analytical method has interesting parallels with CAS and the potential to add to existing cognitive models (Portugali 2011c) used in urban simulation.

9.4. Artificial Intelligence

Within artificial intelligence (AI) research can broadly divided into two methods i.e. the 'symbolic' approach and the 'connectionist' approach. These can be described as top-down and bottom-up respectively. Connectionist approaches have recently seen renewed interest and artificial neural networks have utilised in the fields of visual perception, financial analysis, medicine and language processing. Nouvelle AI, describing systems referring embodied intelligences in the real world has refocused attention on machine sensing from external environments.

New research in data science is likely to impact on the complexity science approaches to the urban by adding initial data capture and analysis stages to processes of modelling and simulation. The area of real interest with Big Data and IoT is the potential for discovery of new methods that close the theoretical and operational gap in the complexity sciences and enable the integration of machine learning and artificial intelligence. The optimism does come with multiple warnings, ranging from the corporate misuse of data to the very real possibilities of technological exclusion.

10. Conclusion

The emergent field of urban complexity provides an alternative epistemological framework for research into urban systems demonstrating temporal, relational and emergent phenomena. From a complexity perspective, the urban is a temporal open system of dynamic flows, demonstrating nonlinear and adaptive phenomena. This system is capable of existing on the edge of chaos and displays evolutionary traits. Transdisciplinary development of and engagement with complexity theory provides the opportunity to overlap typically separate soft and hard science research. The need for this is obvious in that the urban combines natural, social and engineered systems. Concept transfer between disciplines engaged in complexity research is common, but this has come under some scrutiny and rigorous common understanding is required. While new IT enabled data systems are facilitating new areas of urban complexity research, the gap between modelers, analysts and theorists will need to be bridged effectively for the unified development of new methods and theory.

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