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COMPLEXITY THEORIES OF CITIES HAVE COME OF AGE
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Complexity Theories of Cities: Achievements, criticism and potentials[1]

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Complexity theories of cities (CTC) have come of age. What some two and a half decades ago was a narrow stream of studies – written mainly by physicists applying theories from physics – has now become not a flood but an established interdisciplinary research domain engaging urban geographers, planners, urban designers, regional scientists, mathematicians, physicists among others. In addition to the constant flow of articles we start to see attempts at integration in the form of spatial theme issues (*Environment and Planning A*, 2006) and of books (Pumain, 2006; Benenson and Torrens, 2004; Portugali, 2000, 2006; Batty, 2005). In such attempts at integration it is just natural to find appraisals of what has been achieved by CTC in the last two decades and a half.

4.1 Achievements

In the introduction to his *Cities and Complexity* Batty (2005) notes that CTC have provided sound theoretical basis with mathematical formalism to the intuitive ideas

[1] This paper is taken from Chap. 5 of Juval Portugali *Complexity, Cognition and the City*. Forthcoming 2010, Springer, Heidelberg.

suggested by Jean Jacobs (1961) (and I would add Christopher Alexander too) more than 40 years ago. In a recent *Science* article he reiterates this view:

> In the past 25 years, our understanding of cities has slowly begun to reflect Jacobs's message. Cities are no longer regarded as being disordered systems. Beneath the apparent chaos and diversity of physical form, there is strong order and a pattern that emerges from the myriad of decisions and processes required for a city to develop and expand physically. Cities are … par excellence complex systems: emergent, far from equilibrium, requiring enormous energies to maintain themselves, displaying patterns of inequality spawned through agglomeration and intense competition for space, and saturated flow systems that use capacity in what appear to be barely sustainable but paradoxically resilient networks." (Batty, *Science* 8 February 2008:Vol. 319. no. 5864, pp. 769 – 771).

Similar things can be said of the relations between CTC and other "classics of urban studies". Allen's dissipative structures approach to cities, is in a way a reinterpretation and reformulation of Christaller's central place theory in terms of Progogine's dissipative structures, Weidlich's synergetic approach to cities, of Haken's theory of synergetics and just recently the close to 100 years old rank size rule of Auerbach (1913) is being reinterpreted in terms of Barabasi's and Watts' "new science of networks" and its power law distribution.

The major achievement of CTC is thus not so much in identifying new urban phenomena but in giving a single and sound theoretical basis to a variety of urban phenomena and properties that so far were perceived as independent of each other and thus interpreted by reference to different theoretical bases: The pattern of land use in cities that in the past has been interpreted in terms of Thunen's economic theory, the spatial segregation of ethnic, cultural and socio-economic social groups in the city that in the past has been interpreted in urban ecological terms, the size distribution of cities in a region, the economic and geographical spatio-hierarchical pattern of central places in cities, metropolitan regions and countries, the structure of road networks of cities as well as the structure of communication between cities and more urban phenomena, all have today a single theoretical basis; all have already been interpreted as emerging out of local interactions between agents that give rise to global structures and so on.

4.2 Criticism

In early 2008 I was invited by sLIM (http://www.slim.nu/en/lg11introen.php) to give a talk on "The theory of self organization and its potential for addressing the 21st century city both in the developing and developed world". The motivation for this meeting was the observation that the 21st century is marked by a strong sensation of change the signs of which are abundant: Globalization, civil society, privatization, the decline of the national welfare-state and of course cities; cities capture the core of this change: For the first time in human history more than 50% of world population live in cities, several cities around the world turned into mega-cities with population of over 20 million, the economy and sphere of influence of many world or global cities extend beyond the boundaries of their nation state and yet parallel to and within, this trend we see a counter trend toward localization or "glocalization", "shrinking cities" and so on. The above sensation and situation shows itself also in the increasing popularity and dominance of theories and perceptions of reality that emphasis change and instability; in the shifts from modernism to postmodernism, from structuralism to post-structuralism, from constructivism to deconstuctivism, from systems in equilibrium to systems in far from equilibrium, from closed to open systems, from entropy to self-organization and complexity with notions such as chaos, edge of chaos, fractal structure, nonlinearity and the rest (Portugali, 2005).

It is therefore not surprising that some of the basic aspects of 21st society and cities are often described in terms taken from the language of complexity theories and CTC: One prominent example is Castells' (1996) *The Rise of the Network Society* and his notions of *space of flow* and *information city*. A more recent example is Healy's (2007) book *Urban Complexity and Spatial Strategy*. It is important to note that both Castells and Healey are using the notion 'complexity' literally without the theoretical formalism and meaning added to it by complexity theory. On the other hand, Thrift's (1999) in a paper on "The place of complexity" refers to complexity theory itself.

The idea of the students who organized the sLIM seminar was that CTC must have a lot to say about the 21st city. Preparing the talk I realized that while this is indeed the case, so far CTC has said very little about the 21st century city and its specific properties. Most researchers in the domain of CTC preferred and still prefer to focus on rather traditional, conservative and somewhat anachronistic urban issues: central place theory, land use, rank-size distributions of cities, national systems of cities and the like – issues that were dominant in the 1950s and 1960s.

As is well recorded, in the early 1970s the study of cities underwent a kind of a paradigm shift when several students of the quantitative-positivist approach to cities – David Harvey being the most dominant of them – started to criticize their own camp on the ground that the arsenal of scientific theories and methods developed by quantitative urbanists and location theorists is "incapable of saying anything of depth and profundity .." (Harvey 1973, 129) about the real problem of cities in the 1960s and 1970s. The result was a split between the two cultures of urban research and that the hermeneutic-critical approach dominated the field for more than two decades.

Can we or should we draw a parallel between the tension between the two cultures of cities – the scientific and the humanistic – some 48 years ago and today? Is there a ground to say that CTC are "incapable of saying anything of depth and profundity .." about the burning urban issues of the 21st century city – about processes of globalization and glocalization, about the emergence of megacities of over 20 million people, of urban planning and governance in a society with emerging civil society and so on? I don't think so; not only because CTC have a potential (that has yet to be realized) to add new insight to our understanding of 21st century urbanism, but also because it has a potential to go beyond the two cultures of cities and in fact to unite them (Portugali, 2006). On the other hand, I do think that there is a danger that if CTC go in their current direction they will soon become a new version of the old quantitative approach and as such subject to the same criticism leveled at it in the early 1970s.

4.2.1 What went wrong?

What is the current trend of CTC and why it might lead to irrelevant urban studies? The answer in short is that the current trend is to see CTC as a new generation of quantitative urban simulation models (USM) capable of describing, simulating and predicting urban scenarios in an efficient and accurate ways – much better than the old generation of quantitative methods of the 1950, 1960 and 1970s. Implicit in this current trend is the view that what gives the new generation of USM an edge over the old generation is, firstly, the mathematical formalism and simulation methodologies developed by the various complexity theories, in particular cellular automata (CA), agent base (AB), and more recently network models. Secondly, the new computation technologies that enables to run the new and more sophisticated USM and to crunch huge amounts of data.

There is nothing wrong of course in sophisticated simulation models crunching huge quantities of data by means of fast computers. What wrong is, firstly, that simulation models originally designed as media by which to study phenomena of complexity and self-organization became *the* message itself. Secondly, that CTC tend to overlook/ignore the fact that complexity theory is a new science that is critical of the first culture of cities. Thirdly, and as a consequence of the above, that most studies in the domain of CTC are silent about the qualitative message of complexity theories to cities. Fourthly, that students of CTC have indiscriminately applied to cities theories and models originally developed to deal with natural phenomena, ignoring the implications of the fact that cities are not natural phenomena but rather artifacts. Let me elaborate.

4.2.2 The medium is the message

The situation by which USM have become the message shows up in several phenomena and trends. Firstly, CA and AB USM, as noted above, have become the most popular approached to simulate the dynamics of cities. Their popularity stems from the fact that they are intuitively related to the dynamic of cities, simple to use, and easy to run with empirical data. And indeed the insight they added and still add to our understanding of cities is rather important. On the other hand, however, their intensive use is not without a price: The medium has too often become the message; too often complexity theories of cities and cities themselves are seen through the “eyes” of CA/AB models – as theories of cognitively simple interacting agents that in a bottom-up process give rise to cities and systems of cities that are stable and robust. The problem is that urban agents are cognitively complex and cities are not always robust – not if we study their *longue durée*, that is, their long term evolution and dynamics.

Secondly, in their search for statistical data to feed their models practitioners of urban simulation models tend to overlook the non-quantifiable urban phenomena. This is so with respect to “classical” qualitative urban phenomena such as those of the 21st century cities mentioned above and this is so also with respect to classical phenomena of complexity theory. A case in point is the phenomenon of chaos that is not on the agenda of CTC. The reason to my mind is that chaos is hard to identify in cities by means of published statistical data and as a consequence, with few exceptions (e.g. Chen, 2009), there are no applications of chaos theory to cities.

Thirdly, the medium of CA/AB has too often become the message in yet another respect: many students in the domain of CTC and USM tend to employ CA/AB USM as sophisticated predicting devises, overlooking the fact that complexity theories imply that complex systems are essentially unpredictable – the elementary properties of the theory, such as non-linearity, chaos, emergent properties and the like imply unpredictability. By so doing these practitioners of complexity theory run into a paradox: they claim that cities are complex systems but they treat cities as if they were simple systems.

4.2.3 The qualitative message of CT to cities

Most CTC studies ignore the new insight that CT can add to our understanding of cities in general and to the cities of the 21st Century in particular. Batty's discussion about the general message of CTC as described above and few other studies about this issue (Portugali, 2000, 2006) are exceptions that prove the rule. One reason for that has already been suggested above: The qualitative urban phenomena do not lent themselves to quantitative-statistical analysis and thus are of little interest to mainstream CTC: The growth of cities beyond the nation state, the role of civil society in their dynamics, the implications of complexity and self-organization to planning and design, like other burning questions of 21st Century cities, are all "qualitative", with no "hard" data and as such not in mainstream discourse of complexity theories of cities. It must be emphasized that some qualitative urban phenomena can and have been modeled and simulated by means of CTC USM. For example, our FACS models have been employed to study the process by which the urban dynamics entails the emergence of new socio-cultural groups in the city (Portugali, 2000, Chap. 8). However, since there is no simple way to back such models by "hard" quantitative data they are treated as too theoretical or "pedagogic" (Batty, 2005) and as such less attractive.

One might justly argue that every research domain has boundaries and that the above qualitative issues of complex agents and of 21st century cities fall beyond the boundaries and scope of CTC. My view is that this is not the case. One reason for this view is that so far complexity theories were applied to cities only partially, that is, only selected parts of the processes that make a system complex were applied to the domain of cities. A second reason is that CTC have not as yet crossed the boundary of simple, mechanistic applications.

4.2.4 Partial application

If we look at the general domain of complexity theories we can see, firstly, that processes of self-organization are typically associated with three major steps (Fig….): the process of *emergence* by which the local interactions between the parts of the system give rise to a certain complex global structure; the process of *steady state* during which the system maintains its structure by exchanging matter and information with its environment; and the process of *bifurcation* and *phase transition* during which the old steady state collapses, a new process of emergence starts and generates a new steady state.

Secondly, we can observe a trend from comprehensive to specific. We see that while the founding theories, namely Prigogine's dissipative structures and even more so Haken's synergetics, were comprehensive theories, putting full emphasis on all three aspects and long term evolution of complex systems, subsequent theories became more specific. Thus, Bak's self-organized criticality elaborates on the dynamics by which complex systems maintain their steady state, whereas CA and AB focus mainly on the process of emergence – the dynamics by which local interactions give rise to a global structure.

There is nothing wrong, of course, with the above trend as long as the various approaches complement each other – as long as more theoretical viewpoints shed light on the multiple aspects of complex systems. It starts to be problematic, however, when in order to make their point, the new theories and points of views put shade on, or dismiss as not "quantitative" or "scientific" or up to date, previous ones. This is exactly what happened in the domain of CTC. It started with comprehensive complexity theories of cities and urbanization that theorized about both the short and the *longue durée* of cities and urban processes. However, as more and more researchers joined the club, the comprehensive view of cities and urbanism was put aside and the theoretical focus moved to the short term urban phenomena. One result was that CTC became less and less relevant to the general study of the long term qualitative aspects of cities and urbanism – exactly the kind of issues that today typify 21st century cities and urbanism and today stand at the center of interest of the general discourse about cities. Furthermore, as we've seen above, while the comprehensive CTC tended to employ USM as a medium by which to explore the various aspects, in the more specific CTC the medium of USM has become the message and the search after data to feed the models led many to ignore urban phenomena on which there is no easily accessible quantitative data.

4.2.5 Mechanistic versus adaptive application

Complexity theories were originally developed in the sciences and by reference to natural phenomena. Thus, the Benard experiment was employed by Prigogine in developing his dissipative structure, Haken has developed his theory of synergetics by reference to Benard and the phenomenon of the LASER beam, Mandelbrot has developed his theory of fractals by reference to processes that give rise to snow flakes (Koch's algorithm) or to plants (Lindenmayer's algorithm) Bak's theory of self-organized criticality was inspired by the sandpile experiment and so on. All these theories were applied to cities – applied in a *mechanistic* but not *adaptive* way.

Complex systems are often described as *complex adaptive systems*, that is, systems capable of adapting their structure and behavior to the environment into which they enter or are being introduced. A human being is a typical adaptive system. Adaptability is an important property of complex systems resulting from the fact that such systems are open and capable of self-organization. Non-adaptive systems, per contra, maintain their structure irrespective of the environment. Non-adaptability is a property of closed, simple and mechanistic systems. By the notion *mechanistic application* I thus refer to situations by which a theory or notion is being transferred from one domain to the other in a non-adaptive manner, that is, by maintaining its structure irrespective of the specific properties of the new domain.

With few exceptions, most complexity theories were applied to cities in a non-adaptive manner. Part of these applications was made by physicists whose main interest was not cities but the models they applied. This is evident from the fact that many such papers are published in journals such as *Phisica A* … and the like. For these physicists as well as for the editors of the above journals, cities are nothing but another source of data by which one can feed and test the models. The important finding of such studies is that the size distribution of several systems of cities obeys the *power law*, that several cities, metropolitan regions, rail and road networks are *fractals*, that many cities and their road networks are *small world* and so on. Another part of the applications was made by students of cities and urbanism attracted by the opportunity to develop a science of cities that is based on the strong theoretical and methodological foundations of complexity theories. The fruits of the various applications are that today we have the domain of CTC and USM with significant achievements as described above.

And yet, cities are not natural entities such as liquid, light beams, snow flaks, sand-piles or trees and their parts are not atoms or molecules, or sand grains. Cities are *artifacts*, that is, artificial systems – *facts of art* and human culture – and their parts are human beings that unlike sand grains can think, learn, plan, forget, change their mind and their actions and behavior are products of intentions, plans, social and cultural norms, political pressure and the like. These properties enable humans to adapt to their environment and these properties make each human being a complex, self-organizing adaptive system. The fact that CTC and USM tend to overlook this uniqueness of cities entails a twofold problem: First, there is a limit to what can CTC in their present non-adaptive form say about cities – they can say very little on the really interesting and qualitative problems of cities in the 21st century. Second, it has no feedback to complexity theories, no new insight or new contribution to the general domain of complexity theory.

4.2.6 The limits of non-adaptive CTC

CTC show that cities and transportation routes are fractals, that their size distribution obeys the power law, that bottom-up local interactions between simple agents can give rise to complex global patterns of land-use and ethnic segregation and so on. But what does it mean that a city is fractal? That a system of cities is fractal? Why are they fractals and are typified by a power law distribution? What do we learn about cities from the fact that they can be modeled and simulated in a way analogical to sand-grains or trees? Some forty years ago Wilson (1970) has demonstrated that entropy maximization spatial interaction models can mathematically describe a whole set of urban phenomena ranging from transportation, to retail, housing and more. Entropy, as is well known, is a property of closed and simple systems and as such the exact opposite of complex self organizing systems (Prigogine,1997). Nowadays CTC demonstrate that its USM can explain the same set of urban phenomena as properties of open and complex systems and by reference to principles that remind one of what Schrödinger (1944) in his *What is Life?* has termed *negative entropy* or *negetropy*.[2] To what family of models should we believe – to the entropy ones or to the negetropy ones? I make this point not in order to discredit CTC USM, but to emphasis that a best fit between model and data is not enough. The fact that a given model can successfully generate a tree and a city doesn't mean that a city is a tree – it is not.

In 1965 Alexander has published a paper that has since become famous: "A city is not a tree". In this study, Alexander makes a distinction between two ways of thinking about cities: one is in terms of a hierarchy or a tree, and the other in terms of a semi-lattice (Fig. 11.3). The two cities differ from each other in their structure – a tree versus a semi-lattice, and in the processes that created them and that take place in them.

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Fig. …. The distinction between a tree structure (right) and a semi-lattice structure (left) according to Alexander.

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In this article Alexander demonstrates that despite the similarity between the hierarchical structure of a tree and that of a city (or system of cities), a city is a much more complex network than a tree – it has a semi-lattice structure. In the "tree city" each sub-system in the city is independent from all other subsystems of its level, and it can thus interact with them only via a higher order subsystem. In the semi-lattice city there are overlaps between subsystems of the same order, so that interaction can occur vertically, horizontally and in oblique. As noted by Alexander, it is not only the overlap which makes the difference, but

> more important is the fact that the semi-lattice is potentially a much more complex and subtle structure that the tree ..: a tree based on 20 elements can contain at most 19 further subsets of the 20, while a semi-lattice based on the same 20 elements can contain more than 1.000.000 different subsets (Alexander 1965, 382).

[2] E. Schrödinger *What is Life?* Cambridge University Press, Cambridge, 1944.

Students of CTC like to quote this paper because it implies that cities are very complex networks. Alexander wrote about these differences as an urban designer with the aim to negate "natural" to mechanistic cities:

> I want to call those cities which have arisen more or less spontaneously over many, many years *natural cities*. And I shall call those cities and parts of cities which have been deliberately created by designers and planners artificial cities. Siena, Liverpool, Kyoto, Manhattan are examples of natural cities. Levittown, Chandigarh and the British New Towns are examples of artificial cities.

This terminology is to my mind misleading for the simple reason that unlike the *tree* which is by definition a genuine natural entity, Siena, Liverpool Kyoto, Manhatten as well as Levittown, Chandigarh and the British New Towns are all *artifacts*. The more significant question is therefore 'what makes artifacts such as Siena or Kyoto more complex (with a semi lattice network) than the natural entity tree and cities like the British New Towns? The answer is implicit in Alexander's paper:

> For example, in Berkeley at the corner of Hearst and Euclid, there is a drugstore, and outside the drugstore a traffic light. In the entrance to the drugstore there is a newsrack where the day's papers are displayed. When the light is red, people who are waiting to cross the street stand idly by the light; and since they have nothing to do, they look at the papers displayed on the newsrack which they can see from where they stand. Some of them just read the headlines, others actually buy a paper while they wait.
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> This effect makes the newsrack and the traffic light interactive; the newsrack, the newspapers on it, the money going from people's pockets to the dime slot, the people who stop at the light and read papers, the traffic light, the electric impulses which make the lights change, and the sidewalk which the people stand on form a system - they all work together.

They all work together because of the *human agents* that are involved in the dynamics that unlike the traffic lights, the newsrack and the headlines, can see and read from a distance, change their trajectory and buy a newspaper, and by means of these *cognitive capacities* the people, the newspapers, the traffic lights and the other spatially fixed objects form a system – "a unit in the city" as Alexander calls it.

A tree is a typical example of a complex system and a typical example of a fractal structure that can and has been generated by a variety of algorithms including CA (Fig. ..). So far CTC has demonstrated that *a city is a tree*. To go beyond that CTC have to look not only at the similarities between natural and artificial entities but also at their differences. The same applies to the relations between CTC and the more complexity theories at large: as long as CTC will treat cities as trees, as long as they will apply the various complexity theories mechanistically, they will have nothing to add and contribute to general theories of complexity; in order to contribute to this general body, CTC will have to look not only at the similarities between natural and artificial entities but also at their differences (see Wilson, 2006 for the contribution to complexity theory).

4.2.7 Simple versus complex agents

Studies on cities show that many of the properties of urban objects (e.g. land value, cultural image, etc.) are determined by their relations to their nearest neighbors. CA is a model in which the properties of every cell are determined in a similar way: by the cell's relations to its nearest neighbors. This similarity makes CA a rather attractive model to simulate cities. Their disadvantage is that in cities we have in addition to relations between objects/cells relations between the many urban agents. CA cannot simulate these relations, at least not explicitly and it is here where AB models come in – they add to the dynamics of urban objects the action of and interaction between the many urban agents. As the name AB indicates, the agent is the most important entity of this kind of models. But what is an agent in general and in the context of cities in particular?

In *Cities and Complexity* Batty (2005) addresses this issue. Surveying the literature on the history of and meaning of the notion agent he defies agents as

> "… objects that do not have fixed location but act and interact with one another as well as the environment in which they exist, according to some purpose. In this sense agents are usually considered as acting autonomously. … Autonomous agents thus cover a wide variety of behaving objects from humans and other animals or plants to mobile robots …" (209-10).

He then Follows Franklin and Graesser (1997) and classifies agents' action and sensing capabilities as ranging between "passive" agents who can only react to what they encounter in the environment, to "cognitive" agents that in addition to reaction also act according to some protocols and goals. Batty then introduces a set of models that illustrate how AB can become USM … Some of these urban models are reactive, while others are "cognitive". From Batty's survey it is not clear whether or not urban agents are reactive or cognitive nor weather urban agents are similar or different from agents in other domains. Apparently this is so since his models are generative. In fact there is no discussion in the literature of CTC about the nature and meaning of urban agent.

The absence of such a discussion is more sever in face of the fact that since the 1960 we have a research domain called 'cognitive geography' that specializes exactly on this: how human agents perceive and cognize space, how they navigate and behave in space, take location decisions and so on. Apart from a few exceptions, CTC ignore this body of knowledge.

4.3 Potentials

The potential contribution of complexity theories to the general study of cities and urbanism, that has yet to be realized, follows directly from the criticisms discussed above. Two main issues form this potential: The first issue follows the view suggested above that CTC have so far exhausted only some complexity theories, namely, the short-term ones. The potential that has yet to be realized here is thus to elaborate on the long-term qualitative message of complexity theory to cities and to urban theory in general.

The second issue concerns the twofold aspects of adaptive application: Firstly, the fact that all major complexity theories have developed by reference to material or organic natural systems, whereas cities are essentially artificial systems. The second potential is therefore to identify the meaning of this difference and to develop CTC that start from the notion that cities are complex artificial environments. Secondly, the fact that cities are dual complex systems in the sense that each urban agent is itself a complex self-organizing system. The third potential is therefore to identify the meaning of this difference and to develop a cognitive CTC and a cognitive approach to USM.

Concluding notes

CTC is today in a crossroad or to use the language of CT at a bifurcation point. Two main attractors can be observed from this position: One, that CTC should be seen as the second science of cities – more elaborated and sophisticated that the previous one that dominated the field in the 1950s and 1960s for the reasons noted above: It has better technology, strong theoretical basis and better simulation and prediction USM. This first attractor is currently the dominant one as we've seen but it has several sever drawbacks that have been specified above. The second attractor is that CTC will realize its potential and become the link between the two cultures of cities – a point of view I've started to elaborate in a paper entitled "Complexity theory as a link between space and place" (Portugali, 2006) and will further elaborate in subsequent studies.

Bibliography

To be completed