Applications of complexity theory

Urbanisation and complex Systems

by Colin Harrison, IBM Distinguished Engineer Emeritus (retired), formerly lead the development of technical strategy for IBM's Smarter Cities initiative

The city is humanity's greatest invention. An artificial ecosystem that enables millions of people to live in close proximity and to collaborate in the creation of new forms of value. While cities were invented many millennia ago, their economic importance has increased dramatically since the Industrial Revolution until they now account for the major fraction of the global economy. All human life is there and so the study of cities crosses boundaries among economics, finance, engineering, ecology, sociology, anthropology, and, well, almost all forms of knowledge. Yet, while we have great knowledge in each of these domains individually, we have little scientific knowledge of how they come together in the overall system of systems that is a city. In brief: How does a city work?

Such knowledge would be helpful in the coming decades. In the last sixty to seventy years, globalisation has spread the Industrial Revolution ever more widely, creating in cities new opportunities that attract hundreds of millions of internal and international migrants. This process is lifting many of these migrants out of deep poverty, while causing cities from London to Nairobi to struggle in differing ways with the unending influx.

Further, cities are responsible for large fractions of greenhouse gas emissions, for the consumption of natural resources such as water and air, and the resulting discharges of pollution into the environment. If the battle against climate change is to be won, it will be won in cities. Cities are also the principal centres for innovation and economic development, both of which are needed to continue lifting migrants out of poverty.

While the roots of urban planning can be traced back more than three thousand years in terms of the master plans of cities, it was the tremendous growth of cities in the late 19th century that transformed that field into considering the many services and affordances that are required for urban dwellers. But urban planning emerged mainly from the humanities and works primarily through extensive case studies, although it has adopted many digital tools. The notion of the city as an object of scientific study is more recent and still in its infancy, triggered in part by developments in complexity theory such as network theory, scaling laws, and systems science, and the growing availability of urban data.

Urban scaling laws have been explored at least since the early 20th century, when cities were found seen to be an example of Zipf's law. In this case Zipf's Law states that "for most countries, the number of cities with population greater than S is proportional to 1/S". The understanding of scaling was greatly expanded in recent years by the works of West and Bettencourt and Batty. Their work showed that many properties of cities such as the number or lengths of roadways, the numbers of amenities such as restaurants, and so forth follow scaling laws over population ranges from ten thousand to tens of millions. Moreover these scaling laws have exponents in the ranges 0.85 to 1.15 that show large cities to be more productive, innovative, efficient in energy consumption, expensive, but also better paying than small cities. Likewise negative attributes such as crime, disease, and pollution also scale superlinearly, that is they don't rise in strict proportion to the increase in city size. For example, GDP is proportional to the Size (S) of a city raised to a power that is slightly greater than 1, thus $S^{1.15}$, while other attributes like energy consumption per capita scale sublinearly, at $S^{0.85}$. Network laws also describe well the evolution over long time scales of roadways and railways in cities.

While scaling laws and network laws have great descriptive power, opinions vary on whether they apply across different countries or have predictive power. That is, the scaling of attributes is a snapshot of frequency versus size at a given time. If a city grows and "moves up the scale", it may not achieve, in the short term, all of the positive benefits and negative impacts described. Nor do the laws provide explanations for the observed behaviours. Nonetheless, this is an important area for planners and developers seeing their cities growing or shrinking.

As urban data has become more pervasive, it is now possible to study cities as complex systems of interactions. We may view the city as a myriad of interactions among its inhabitants, its infrastructures and affordances, its natural environment, and its public, private, and civic organisations. Some of these interactions involve the exchange of goods or services for money, but many of them involve the exchange or transmission of information, enabling inhabitants and organisations to make choices. Public transportation is often studied in this way, revealing for example that small- and medium-sized cities evolve networks enabling commuting between small numbers of residential and business districts, while very large cities, such as London, have much richer networks that permit greater flexibility in where people live and work.

The operation of cities is also modelled using synthetic populations of software agents that represent the distribution of behaviours or preferences of much larger, real populations. Such agent-based models, with agents representing patterns of origin, destination, travel times, and modality preferences, are used to examine the overall impact of new services such as London's Crossrail.

As the Internet of Things provides greater visibility into how inhabitants choose to exploit the opportunities offered by a given city, we may hope to discover abstract principles about how cities work. We may envision being able to construct agent-based models representing the complete spectrum of choices a city's inhabitants make at timescales from minutes to years and spatial scales from meters to kilometres. Equally, given the increasing availability of real-time information, we might hope one day to understand the effective use of a city's services in terms of a Nash Equilibrium, a game theory concept (often used to describe poker games), where no player can gain anything by changing their chosen strategy if other players don't change theirs – all the players' strategies are optimal. These are far in the future, but the European Commission's Global Systems Science programme is the beginning of that journey.

Useful links

The original article on OECD Insights, including links and supplementary material, can be found here: *http://wp.me/p2v6oD-2Cx*

The full series can be found here: *http://oecdinsights.org/?s=NAEC+complexity*

Big Data, complexity theory and urban development

by Ricardo Herranz, Managing Director, Nommon Solutions and Technologies, Madrid

We are living in the era of cities: more than 50% of the world population is already living in urban areas, and most forecasts indicate that, by the end of this century, the world's population will be almost entirely urban. In this context, there is an emerging view that the global challenges of poverty eradication, environmental sustainability, climate change, and sustainable and secure energy are all intimately linked to cities, which are simultaneously places where these global problems emerge and solutions can be found. In the short term, cities are facing the major challenge of overcoming the financial and economic crisis and emerging stronger from it. In the long term, they need to deal with structural challenges related to globalisation, climate change, pressure on resources, demographic change, migration, and social segregation and polarisation. Many of these challenges are shared by cities from developed and developing countries, while others depend on geographical, institutional, socio-economic and cultural differences.

When addressing these problems, policy makers and society at large face a number of fundamental problems. The many components of the urban system are strongly interwoven, giving rise to complex dynamics and making it difficult to anticipate the impact and unintended consequences of public action. Cities are not closed systems, but they are part of systems of cities. Urban development policies are subject to highly distributed, multi-level decision processes and have a profound impact on a wide variety of stakeholders, often with conflicting or contradictory objectives.

In the past few years we have seen the emergence of concepts such as the smart city, urban informatics, urban analytics and citizen science, which are seen to hold great promise for improving the functioning of cities. However, arguably most of this potential still remains to be realised. The concept of the smart city has been coined as a fusion of ideas about how information and communication technologies can help address critical issues relating to cities.

Essential to this concept is the notion of an integrated approach to the synergies and trade-offs between different policy domains that are closely interrelated, but have traditionally been addressed separately, such as land use, transport and energy. This integrated approach would be facilitated by the ability to analyse the increasingly large data streams generated by the ubiquitous sensorisation of the built environment and the pervasive use of personal mobile devices. In parallel, smart devices and social media are also producing new forms of public participation in urban planning. The opportunities are vast, but so are the challenges.

Much hope has been placed in the explosion of Big Data for establishing the foundations of a new science of cities. During the last 20 years, the dominant trend in urban modelling has changed from aggregate, equilibrium models to bottom-up dynamic models (activity-based and agent-based models) that seek to represent cities in more disaggregated and heterogeneous terms. This increasing model sophistication comes with the need for abundant, fine-grained data for model calibration and validation, hindering the operational use of state-of-the-art modelling approaches. The emergence of new sources of Big Data is enabling the collection of spatio-temporal data about urban activity with an unprecedented level of detail, providing us with information that was not available from surveys or census data. This has already yielded important practical advances in fields like transportation planning, but it is more questionable, at least for the moment, that Big Data has produced substantial advances in our understanding of cities. In principle, the potential is there: while research on cities has historically relied on cross-sectional demographic and economic datasets, often consisting of relatively small samples, we have now large-scale, detailed longitudinal data that can allow us to test new hypotheses about urban structure and dynamics. On the other hand, there is a risk that Big Data leads to a shift in focus towards short-term, predictive, non-explanatory models, abandoning theory. Connecting the smart city and Big Data movements with the knowledge developed in the last decades in fields like regional science, urban economics and transportation modelling appears as an essential condition to overcome this problem and take advantage of the opportunities offered by Big Data for the formulation of better theories and policy approaches.

Both empirical work and theoretical advances are needed to cope with the new challenges raised by energy scarcity and climate change, emerging technologies like self-driving cars, and the changes in social relationships, the new activities and the new forms of sharing economy enabled by social media and electronic communications, among other factors that are leading to profound changes in urban structure and dynamics. Equally challenging is to integrate data and models into governance processes: policy assessment and participatory planning are still largely based on qualitative considerations, and there is a sense that state-of-the-art urban models are immature with respect to institutional integration and operational use. New forms of data sharing and visualisation, digital participation and citizens' engagement are promising tools to tackle this question, but here again, we still have to figure out how to share data and specialised knowledge in a form that fluidly intersects participatory decision making process and bridges the gap between implicit and explicit knowledge. Recent advances in areas such as network theory, agent-based computational modelling and group decision theory, and more generally the intrinsically holistic and eclectic approach advocated by complexity science, appear as a suitable framework for the development of a new science of cities which can in turn lead to new advances in the way cities are planned and managed, allowing us to address the enormous challenges related to urban development in the 21st century.

Useful links

The original article on OECD Insights, including links and supplementary material, can be found here: *http://wp.me/p2v6oD-2Di*

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Innovation and complexity

by Andrew Wyckoff, Director, OECD Directorate for Science, Technology and Innovation

Since its creation in 1961, the OECD has influenced how governments approach science, technology and innovation, and how economics as a discipline tries to understand these phenomena. The OECD Working Party of National Experts on Science and Technology Indicators (NESTI) was created in 1962, and in 1963, *Science, economic growth and government policy* convinced governments that science policy should be linked to economic policy. In 1971 *Science, growth and society* (also called the *Brook Report* after the Chair, Harvey Brooks) anticipated many of today's concerns by emphasising the need to involve citizens in assessing the consequences of developing and using new technologies.

For many experts though, the major contribution was the concept of national innovation systems, presented in 1992 in a landmark publication, *Technology and the Economy: The Key Relationships*. The origins of the concept go back to the 1970s crisis, which had provoked an in-depth re-examination of previous economic thinking on how growth came about and why growth in productivity was slowing. A 1980 OECD report, *Technical Change and Economic Policy*, is now widely recognised as the first major policy document to challenge the macroeconomic interpretations of the 1970s crisis, and to emphasise the role of technological factors in finding solutions, arguing for instance that innovation can be more powerful than wage competitiveness in stimulating an economy.

Economists working at the OECD were pioneers of a new approach that saw innovation not as something linear but as an ecosystem involving interactions among existing knowledge, research, and invention; potential markets; and the production process. In national innovation strategies, one of the key issues is the interactions among the different actors: companies, public research institutions, intermediary organisations, and so on. And contrary to the dominant thinking in policy circles in the 1980s and early 1990s, the OECD also saw it as something that governments should play a central role in – hence the term national innovation strategy.

Today, services are becoming the focus of innovation, with some companies even blurring the distinction between the value-added of products and services, smartphones being a good example. This is a logical outcome of the increasing digitalisation of the economy. Digital technologies are now so ubiquitous that it is easy to forget how recent they are. The World Wide Web we know today for example was created in the 1990s, and Microsoft thought it was possible to launch a rival to Internet (called MSN) as late as 1995. Google was only founded in 1998 and it would be 6 years before it went public.

With the digital economy and society coming so far in such a short time, it is hard to predict what they will look like in the future. We can however identify some of the drivers of change. Big Data will be among the most important. In *The phenomenon of data-driven innovation*, the OECD quotes figures suggesting that more than 2.5 exabytes (EB, a billion gigabytes) of data are generated every single day, the equivalent of 167 000 times the information contained in all the books in the US Library of Congress. The world's largest retail company, Walmart, already handles more than 1 million customer transactions every hour. Because so many new data are available, it will be possible to develop new models exploiting the power of a complexity approach to improve understanding in the social sciences, including economics. Also, the policy-making process may benefit from new ways of collecting data on policies themselves and vastly improving our evaluation capabilities.

The analysis of data (often in real time), increasingly from smart devices embedded in the Internet of Things opens new opportunities for value creation through optimisation of production processes and the creation of new services. This "industrial Internet" is creating its own complex systems, empowering autonomous machines and networks that can learn and make decisions independently of human involvement. This can generate new products and markets, but it can also create chaos in existing markets, as various financial flash crashes have shown.

Two sets of challenges, or tensions, need to be addressed by policy makers to maximise the benefits of digitally-driven innovation, and mitigate the associated economic and societal risks. The first is to promote "openness" in the global data ecosystem and thus the free flow of data across nations, sectors, and organisations while at the same time addressing individuals' and organisations' opposing interests (in particular protecting their privacy and their intellectual property). The second set of tensions requires finding policies to activate the enablers of digital-driven innovation, and at the same time addressing the effects of the "creative destruction" induced by this innovation. Moreover, there is a question concerning the efficacy of national policies as digital-driven innovation is global by definition. As a policy maker you can promote something in your country, but the spillovers in terms of employment or markets can be somewhere else.

With so many new technologies being introduced, more firms and countries being integrated into global value chains, and workers becoming more highly educated everywhere, you would expect productivity growth to be surging. In fact it is slowing. But that average trend hides the true picture according to an OECD study on The Future of Productivity. Labour productivity in the globally most productive firms ("global frontier" firms) grew at an average annual rate of 3.5% in the manufacturing sector over the 2000s, compared to 0.5% for non-frontier firms.

Diffusion of the know-how from the pioneering frontier firms to the bulk of the economy hasn't occurred – either because channels are blocked or because we are in a transformative period and the expertise for how best to exploit the technologies is still in the heads of a few. Most likely, it is a combination of the two. We therefore have to help the global frontier firms to continue innovating and facilitate the diffusion of new technologies and innovations from the global frontier firms to firms at the national frontier. We can try to create a market environment where the most productive firms are allowed to thrive, thereby facilitating the more widespread penetration of available technologies and innovations. And we have to improve the matching of skills to jobs to better use the pool of available talent in the economy, and allow skilled people to change jobs, spreading the know-how as they move.

In a complex system, you can't forecast outcomes with any great degree of certainty, but many of the unintended outcomes of interactions in the innovation system are beneficial. The policies mentioned above would each be useful in themselves and would hopefully reinforce each other beneficially.

Useful links

The original article on OECD Insights, including links and supplementary material, can be found here: *http://wp.me/p2v6oD-2Ff*

The full series can be found here: *http://oecdinsights.org/?s=NAEC+complexity*

Governing education in a complex world

by Tracey Burns, Project Leader, *OECD Directorate for Education and Skills*

The famous slogan “KISS” urges listeners to “Keep it simple, stupid!” However, modern policy making is increasingly discovering that *not* keeping it simple – in fact, embracing the *complex* – is essential to understanding contemporary systems and making reform work.

Modern societies are made up of a growing number of diverse stakeholders who collaborate through formal and informal channels. The rapid advancement and reach of information and communication technologies has enabled them to play a much more immediate role in decision-making while at the same time the delivery of public services has become more decentralised.

This complexity brings a series of dynamics that the traditional policy cycle is not able to capture. This is not startling news: numerous critics have described the inadequacy of the traditional policy cycle in agriculture, medicine, and education for the last 30 years. What has changed, however, is a growing understanding across a much broader set of actors that we can no longer continue to operate using traditional linear models of reform.

This is not just a theoretical discussion: ignoring the dynamic nature of the governance process makes reform less effective. In education for instance, even very similar schools can react quite differently to the same intervention. A case study of the Netherlands demonstrated how some weak schools benefitted from being labelled as in need of improvement, coming together as a school community to set off a virtuous cycle to improve performance. In contrast other schools struggled when faced with the same label, with some descending into vicious cycles where teachers felt unmotivated, parents moved their children to another school, and overall performance declined. A simple model of reform and governance cannot account for this complexity.

How can complexity be identified? A seminal 2002 paper by Glouberman and Zimmerman distinguishes between three types of problems: the *simple*, the complicated, and the complex. A simple problem is, for example, baking a cake. For a first time baker, this is not easy, but with a recipe and the ingredients you can be relatively sure that you will succeed. Expertise here is helpful, but not required.

In contrast, a *complicated* problem would be sending a rocket to the moon. Here, formulas are essential and high level expertise is not only helpful, but necessary. However, rockets are similar to each other in critical ways, and once you have solved the original complicated problem, you can be reasonably certain that you'll be able to do it again.

Both simple and complicated problems can be contrasted with a *complex* problem, such as raising a child. As every parent knows, there is no recipe or formula that will ensure success. Bringing up one child provides useful experience, but it is no guarantee of success with another. This is because each child is unique and sometimes unpredictable. Solutions that may work in one case may only partially work, or not work at all, in another.

Returning to the failing school example, it was the unpredictability of the dynamics inherent in the response of the schools and their communities that rendered the problem complex as opposed to merely complicated. Acknowledging the complexity inherent in modern governance is thus an essential first step to effective reform.

Successful modern governance:

- *Focuses on processes, not structures*. Almost all governance structures can be successful under the right conditions. The number of levels, and the power at each level, is not what makes or breaks a good system. Rather, it is the strength of the alignment across the system, the involvement of actors, and the processes underlying governance and reform.
- *Is flexible and able to adapt to change and unexpected events*. Strengthening a system's ability to learn from feedback is a fundamental part of this process, and is also a necessary step to quality assurance and accountability.

- *Works through building capacity, stakeholder involvement and open dialogue*. However it is not rudderless: involvement of a broader range of stakeholders only works when there is a strategic vision and set of processes to harness their ideas and input.
- *Requires a whole of system approach*. This requires aligning policies, roles and responsibilities to improve efficiency and reduce potential overlap or conflict (e.g. between accountability and trust, or innovation and risk-avoidance).
- *Harnesses evidence and research to inform policy and reform*. A strong knowledge system combines descriptive system data, research findings and practitioner knowledge. The key knows what to use, why and how.

Creating the open, dynamic and strategic governance systems necessary for governing complex systems is not easy. Modern governance must be able to juggle the dynamism and complexity at the same time as it steers a clear course towards established goals. And with limited financial resources it must do this as efficiently as possible. Although a challenging task, it is a necessary one.

Useful links

The original article on OECD Insights, including links and supplementary material, can be found here: *http://wp.me/p2v6oD-2D9*

The full series can be found here: *http://oecdinsights.org/?s=NAEC+complexity*

Development as the outcome of a complex adaptive system

by Frans Lammersen and Jorge Moreira da Silva (Director),
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In *The Wealth of Nations*, Adam Smith wrote that: "Little else is requisite to carry a state to the highest degree of opulence from the lowest barbarism but peace, easy taxes, and a tolerable administration of justice: all the rest being brought about by natural course of things." Others were less optimistic. They argued that nations are rich or poor because of differences in religion, culture, endowments, and/or geography.

Modern economic development theories originate from thinking about how to reconstruct Europe in the aftermath of World War II. The European Recovery Program – or the Marshall Plan – was based on the notion that economic growth can be stifled by local institutions and social attitudes, especially if these influence the domestic savings and investments rate. According to this linear growth model, a correctly-designed massive injection of capital coupled with public sector intervention to address market failures would ultimately lead to industrialisation and economic development. Many other economic development theories have since followed, but none have been able to explain convincingly why some countries experience rapid economic growth and others not.

The development community has continued its quest for the missing ingredient to ignite economic growth. Candidates have included capital, technology, policies, institutions, better politics, and market integration. Every time we think we have identified what's missing, we find that it is actually not something which can be provided from outside, but turns out to be an endogenous characteristic of the system itself. Traditionally, development assistance has been rooted in a type of engineering, mass production, conveyor belt mentality, with agencies promoting "silver bullet" solutions for such complex problems as eradicating malaria, reducing vulnerability, improving resilience, strengthening connectivity etc. Unfortunately, piecemeal or one step at a time development programmes often failed to deliver.

Increasingly, complexity thinking – a way of understanding how elements of systems interact and change over time – has found its way into the development discourse. After all, what could be more complex than promoting development, sustainability, human rights, peace, and governance? We should think of the economy and society as being composed of a rich set of interactions between large numbers of adaptive agents, all of which are coevolving. Based on this approach development is not just an increase in outputs, but the emergence of an interlinked system of economic, financial, legal, social and political institutions, firms, products and technologies. Together these elements and their interaction provide citizens with the capabilities to live happy, healthy and fulfilling lives.

Once we look at development as the outcome of a complex adaptive system instead of the sum of what happens to the people and firms, we will get better insights into how we can help accelerate and shape development. We would be more effective if we assess development challenges through this prism of complex adaptive systems. This could yield important insights about how best to prioritise, design and deliver holistic development programmes for achieving the multiple goals of inclusiveness, sustainability and economic growth that underpin the 2030 Sustainable Development Agenda. There is increasing support in aid agencies for the idea that solutions to complex problems must evolve, through trial and error – and that successful programmes are likely to be different for *each local context*, with its particular history, natural resources and webs of social relations. The key for anyone engaged in the aid business is to put their own preconceived ideas aside and first observe, map, and listen carefully to identify the areas where change for the better is already happening and then try to encourage and nurture that change further.

Complexity matters particularly when the knowledge and capacities required for tackling problems are spread across actors without strong, formalised institutional links. Inherent to many complex problems are divergent interests, conflicting goals or competing narratives. Moreover, it is often unclear how to achieve a given objective in a specific context, or change processes that involve significant, unpredictable forces. At the same time, it is important to emphasise that the counsel of complexity should not be taken as a counsel of despair for development. There has been immense social and economic progress, and development assistance has found to be helpful overall. Development co-operation has contributed to achieving economic objectives by helping developing countries connect their firms to international markets; to achieving social objectives by making globalisation pro-poor and reducing inequalities; and to environmental objectives by adapting to climate change while exploiting comparative advantages.

Not all development challenges are inherently complex though. For those that are, complexity should not be used as an excuse for fatalism and inertia. Instead we should strive to promote innovation, experimentation and renewal. We should build partnerships to learn about the past, allowing us to shape approaches that are more likely to work and that are owned by the people we are trying to help. They will tell us what is working and what is not. Together we should build a narrative for change involving many different voices and perspectives. We should also be modest and realise that it might better to start small and learn and adapt as we go along in iterative processes of dialogue. We should keep looking for change, scanning widely for new factors emerging in the wider world; listen to a wide range of opinions to be better able to anticipate and adapt and seize opportunities.

Embracing complexity where it matters will allow us to contribute more effectively to the 2030 Sustainable Development Agenda.

Useful links

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