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Managing the Interrelations Among Urban Infrastructure, Population, and Institutions

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Das Forschungszentrum Nachhaltigkeit (artec) – Kurzportrait

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- **Was kann erkannt und getan werden, um die Verletzlichkeit sozialer und natürlicher Systeme zu reduzieren?**
- **Was ist nötig, um deren „Abwehrkräfte“ zu steigern?**

Die Hauptkompetenzen liegen in den Bereichen: Arbeitswissenschaft, Technikfolgenabschätzung und Technikbewertung, Managementlehre, Unweltsoziologie und Umweltpolitik.

Integration, Interdisziplinarität und Gestaltungsorientierung bilden die Leitorientierungen für Forschung und Beratung und es werden verschiedene konzeptionelle Zugänge zur Nachhaltigkeitsproblematik quer zum Disziplinbezug verfolgt. Die Forschung wird gegenwärtig in vier interdisziplinär ausgerichteten Forschungsfeldern durchgeführt:

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(Guido Becke, Eva Senghaas-Knobloch)

2. Nachhaltigkeitsmanagement und Unternehmensentwicklung

Effizienz und Nachhaltigkeit; Probleme der strategischen Planung nachhaltiger Unternehmensentwicklung und Kooperationsperspektiven.
(Georg Müller-Christ, Brigitte Nagler)

3. Nachhaltigkeitsorientierte Technikentwicklung und -bewertung

Stoffstrommanagement und Kreislaufwirtschaft, technikorientierte Leitbildforschung und sozialwissenschaftliche Untersuchung der Technikgenese und -regulierung mit Blick auf moderne Schlüsseltechnologien.
(Arnim von Gleich, Hans Dieter Hellige, Ulrich Dolata)

4. Nachhaltigkeit in Kommune und Region

Entwicklung nachhaltiger Handlungsmuster und Strukturen in Politik und Verwaltung, Routinen der persönlichen Alltagsgestaltung und -organisation, Konsummuster und Lebensstile.
(Hellmuth Lange, Ines Weller)

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Abstract

Increases in urban populations, aging infrastructures and global environmental change have begun to highlight the need and urgency to address urban resilience through research and stakeholder-based dialog. The number of case studies for individual locations and on individual challenges – such as meeting water or energy demands – are increasing. Many of those studies reveal the complexity of managing interrelations among population, infrastructure, and institutions, though many ultimately choose a narrow, sector-specific approach to the issue. Few approaches have built on insights from complexity theory and related bodies of knowledge which are more consistent with the perspective that urban infrastructure systems are tightly coupled with one another and must respond to often subtle, long-term changes of technological, social and environmental conditions. Drawing on that knowledge, and building on insights from previous case studies, this paper explores the potential roles of complexity theory in guiding investment and policy decisions in the urban context, focusing on strategies to promote resilience and adaptability in the light of population, infrastructure, and institutional dynamics.

Key Words

Urban resilience, complex systems, infrastructure, global change, environmental impact, adaptive management

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1. Introduction

As the number of people and the volume and intensity of economic activities in cities are growing worldwide, the influences of cities on the local and global environment are rising. The repercussions of that environmental change, in turn, are felt by the inhabitants of cities and their hinterlands, as well as by the economic sectors that sustain livelihoods. Traditional urban analysis has focused on the individual drivers behind urban change and individual impacts on people, the economy, and the environment (e.g., Robson 1969, Dear and Dishman 2002). Although urban systems analysis is often rich in empirical detail or theoretical conceptualizations dealing with both the temporal and spatial dimensions of urban change (e.g. Black and Henderson 1999, Fujita et al. 1999, Brenner 2000), the interconnection among the various drivers and repercussions – social, economic, and environmental – frequently has been acknowledged but rarely has become, in its own right, the object of analysis. Where the focus truly has been on the complexity of urban change, the products were often either computer-based exercises or conceptual frameworks. Most popular among the former are simulation games, such as SimCity™ (EAI 2005), which concentrate on the evolution of a hypothetical or stylized urban system. In such games, a single player typically interferes in a system's dynamics through various choice variables and learns to appreciate the complexity and uncertainty inherent in system intervention.

Examples of systematic, theory-based conceptualizations of urban change include work by Peter Nijkamp and colleagues (e.g. Nijkamp and Reggiani 1992, Camagni et al. 1998), Jan Rotmans (1994, 2006), Michael Batty (2005), Patsy Healey (2007 in press), and a large number of others, many of whom have begun to view urban dynamics through the lens of modern complexity theory. Some of the recent research in this area illustrates a merger between urban simulation and complex systems analysis, by explicitly basing computer simulations of urban dynamics on, and interpreting outcomes of urban dynamics from the perspective of complexity theory. We will briefly discuss some of these studies in more detail below.

More recently, a new flavor of urban analysis has developed, one that is pragmatic in nature and that combines, among other approaches, theoretical, empirical, simulation-based, and stakeholder-guided assessments. The pragmatic aspect of the research lies in the identification and study of issues relevant to decision makers, and in efforts to make findings relevant to the decision making process. Much of that work has been spawned by the debate about regional impacts of, and adaptations to climate change (Ruth 2006a). While promising in many regards, several challenges remain for that work to be academically rigorous and, at the same time, relevant for investment and policy making. The discussion below addresses the state of the art, critically summarizes the promises that integrated analysis holds for advancing knowledge and improving decision making in the urban context, and highlights the main challenges that remain.

With the intent to contribute to the advancement of urban systems analysis for the management of urban systems, this paper first briefly reviews key drivers of urban change. Here we concentrate on general urbanization trends, changes in urban metabolism, the role and state of infrastructure, urban environmental quality, and urban quality of life. The subsequent section discusses two sets of complementary approaches to better understand complex urban change processes – one predominantly from the perspective of the basic sciences, the other from a more policy-oriented, integrated assessment approach. That discussion raises issues germane to the study of complex systems, which we address in Section 4 of the paper. We close with a brief summary and conclusions.

2. Drivers and Impacts of Urban Change

2.1 Urbanization Trends

Urbanization, though characterized by significant regional differences, is following an overwhelming upward trend. The world has seen a fifteen-fold increase in urban populations since the beginning of the twentieth century, with total urban-dwellers numbering close to three billion in 2000, roughly half of the global population. These three billion people occupy only 2.8 percent of the total land area of the earth, but exert locally and globally significant influence on ecosystems and the well-being of human populations within and outside of their borders. In 2000, as measured by the United Nations (UN) Global Rural-Urban Mapping Project (GRUMP), approximately 37 percent of the populations in Africa and Asia were urban (UNDP 2003). The number is closer to 75 percent in Latin America and the Caribbean, North America, Europe, and Oceania (McGranahan and Marcotullio 2006). As can be seen in Table 1, both total population and urban population at all levels of development are increasing, though at a decreasing rate. Consistently, wealthier and more developed nations are characterized by greater levels of urbanization, though the majority of urban *growth* is occurring in lesser developed nations. Indeed, urbanization in the least developed places is as much as four times that in the most developed nations.

A great deal of attention recently has been given to mega-cities (10 million or more people), but this focus is somewhat inflated; about half of the world's urban population lives in cities of less than 500,000 people, and the majority of urban growth is occurring in medium-sized cities (McGranahan and Marcotullio 2006). In fact, some of the world's largest cities have experienced slowed growth rates in recent decades. This is not to diminish the fact that the average size of the world's 100 largest cities has increased from 200,000 in 1800 to 5 million in 1990 (Cohen 2004). This trend is anticipated to continue as transportation and communication networks, two of a city's most extensive infrastructure systems, expand outside of traditional inner city boundaries.

The age composition within nations and within cities is also changing, with populations aging across the board. That demographic change has far-reaching implications for migration to and from cities, demand for urban infrastructure, urban material and energy use, environmental quality, and quality of urban life. The most pronounced change is seen in middle income and medium human development nations where between 2001 and 2015 UN projections are for an almost 17 percent decrease in the percentage of the population under the age of 15, and a more than 25 percent increase in the percentage of the population over the age of 65. Decreases in youth populations of 12 and 6 percent are anticipated in high and low human development nations, respectively. Increases of 23 and 7 percent in the elderly population are anticipated in these nations.

In addition to purely demographic changes are a suite of environmental conditions that are influencing and being affected by urbanization. Most cities are located in, and are growing primarily in coastal zones, in part because of the importance of access to natural resources and transportation networks in an increasingly globalizing world. Population densities in coastal areas are approximately 45 percent greater than global average densities (McGranahan and Marcotullio 2006). For example, 32 percent of Sri Lanka's total population resides in coastal zones, 65 percent of the urban population, 90 percent of industrial units, and 80 percent of all tourist infrastructure (UNEP 2001c). Clearly stated in the Millennium Ecosystem Assessment report: "As people are increasingly living in cities, and as cities act as both human ecosystem habitats and drivers of ecosystem change, it will become increasingly important to foster urban systems that contribute to human well-being and reduce ecosystem service burdens at all scales" (McGranahan and Marcotullio, p797).

2.2 Urban Infrastructures and Institutions

Adequate supply of infrastructure systems and services, such as water, sanitation, power, communication, and transportation, allows cities to grow and prosper. In some regions, particularly in Africa and Asia, very basic deficiencies characterize urban systems of all sizes. According to some estimates, as much as 50 percent of the urban population in Africa and Asia may be living without "adequate" provision of water and sanitary services. In many of these areas single points of service (i.e. water pumps or latrines) are shared by dozens or hundreds of individuals, significantly limiting sufficient access and safety. Similarly, solid waste disposal, wastewater treatment and transportation networks are frequently insufficient and poorly maintained (see, e.g. UNEP 2001b, c).

However, the challenges of inadequate or declining infrastructures are not confined to the developing world. In some developed nations, particularly Australia, public spending on infrastructure has decreased over the last few decades. Private investment in the provision of electricity and water has increased, but distribution suffers from decentralized services, and concerns abound over the ability of profit-seeking firms to equitably provide public services such as water and transportation (Newton 2001). This concern is pervasive not only in Australia, but in other nations as well (WDR 2006). In the U.S., infrastructure systems have regularly received “poor” or “failing” grades in report cards issued by the American Society of Civil Engineers (ASCE 2005). ASCE evaluates infrastructure systems based on condition and performance, as well as capacity and funding with respect to need. Based on their analysis, there has been little to no improvement since 1998, and there are some $1.6 trillion in recommended infrastructure improvements over a five-year period.

It is the role of institutions, such as government and planning agencies, markets and non-government organizations to anticipate and assess the adequacy of existing infrastructure and the desirability of new infrastructure, to facilitate decision making, and to oversee implementation, operation, maintenance and decommissioning of infrastructure systems. This is particularly crucial in cities, given the close spatial and functional relationships among the various social, economic and environmental processes. Challenges in fulfilling that mission often are related to inabilities to secure adequate funds, inequitable access, the lumpiness and irreversibility of infrastructure investments, and the roles of risk, uncertainty and surprise in investment decision making. Each challenge is discussed briefly here, before we proceed to turn to the ramifications of urbanization for material and energy use, environmental quality, and quality of life.

2.2.1 Infrastructure Investment

Typically, large-scale infrastructure investments are undertaken by government to provide public goods. Examples include the building of dams, wastewater collection and treatment systems, energy supply systems, ports, and roads. However, investment by private enterprises in infrastructure systems should not be overlooked. Notable examples include investments in communication and data storage capacity that made possible the explosion in information exchange and internet commerce. While public investments are typically funded with long-term bonds or loans and with the goal of providing public goods, private infrastructure investments are usually made with much shorter time periods in mind, and with greater attention towards pay-off to the investing parties.

Increasingly, public-private partnerships are used to leverage access to capital with clear profitability goals in mind, while at the same time creating synergistic effects among infrastructure investments, regional competitiveness, and larger-scale socioeconomic development. For example, funding for transportation networks or wastewater treatment may come in part from private enterprises who may, in return, receive revenues from user fees. Private investment in electricity and telecommunications infrastructure in Latin America has increased access to services; however overall public investment in infrastructure fell from three percent of GDP in 1980 to less than one percent in 2001 (WDR 2006). Local authorities may help support the development of eco-industrial parks so that a range of diverse businesses can allocate in close proximity to one another in order to close material cycles, reduce cost of material inputs and minimize effluents while at the same time offering centralized employment opportunities and improved environmental quality. The reduction in investment risk is spread across different parties, allowing for longer planning horizons than would be chosen by private enterprises under normal circumstances.

However, under any model – purely public, purely private, or public–private partnerships – few provisions are typically made to deal with the cost associated with decommissioning infrastructure at the end of its useful lifetime or the cost of retrofitting after expiration of bonds or loans. As a result, the time-delayed burden to deal with the legacy of obsolete infrastructure is often placed on future generations, which considerably contributes to the complexity of urban dynamics and adds challenges to future decision making.

2.2.2 Equitable Access to Infrastructure Systems and Services

Criteria for equality and fairness must include the needs of current and future businesses and households at different locations in the economic landscape. While their needs for infrastructure services will influence the choice of location and type of infrastructure systems, the reverse holds as well – once put in place, infrastructure will affect economic performance of businesses and income of households, as well as their need for infrastructure services. Access to infrastructure, in turn, determines access to resources (natural and human made) and thus affects quality of life.

As a consequence, equality and fairness in space are closely related to equality and fairness through time and across different parts of the socioeconomic system (small and large producers, households from different income groups, etc.). These interrelationships are particularly pronounced in the development of urban relative to rural infrastructure. With urbanization increasing across the globe, the danger exists to concentrate infrastructure development in urban areas at the expense of investing in their surroundings.

The international community recognizes differential mobility, access to education, provision of clean water and sanitary sewer service, life expectancy, and exposure to disease between urban and rural areas, particularly to the extent that greater poverty is associated with rural areas (WDR 2006). For example, enlarged transportation networks require dealing with drainage of water from impervious surfaces, handling construction waste and managing larger traffic volumes. The presence or enlargement of one type of infrastructure system begets investments in another. Increased economic activity in cities and suburbs promotes attraction of companies and consumers alike to urban areas. Several consequences may be felt. Enlarging the urban–rural divide, with growing income differentials, may reduce the sustainability of rural life – undermining cultural and socioeconomic integrity. Conversely, high concentrations of people and economic activities may result in diseconomies of agglomeration, such as congestion, social friction, and consequently an unsustainable urban system.

The rate of change in urban densities themselves can make it virtually impossible for planners and investors to take a long view on infrastructure investment – current efforts to provide infrastructure may be too low to keep up with current growth in population and economic activity, let alone be able to adequately address future needs or long-term environmental concerns. Those problems are exacerbated by the fact that the very activity of creating new infrastructure – both *hard* structures, such as bridges and sewer systems, as well as the *soft* structures of institutions – disrupts the performance of already existing systems. For example, expanding or building a new transportation route, almost certainly, will affect accessibility and operation of existing routes. Creating new bureaucracies inevitably raises, at least in the interim, information and transaction cost. But there is also the possibility for infrastructure change to leap frog, as the example of wireless telecommunication technology in many transition economies shows, its development skipping intermediate stages observed in already developed nations.

2.2.3 Dealing with Indivisibilities, Complementarities and Irreversibilities in Investment

Infrastructure systems, such as water supply, flood control, and transportation networks are typically large and often function as a whole or not at all. A break in a water main, dike, or bridge can render the respective system incapable of providing a service. Investment in redundancy is key to being prepared for disruptions, such as during construction or an emergency. For example, having well-developed private transportation, bus, and rail systems in place can help to cut down on traffic jams in case one of the three is disrupted. Investing in redundancies, however, is costly. Similarly, ensuring adequate and reliable performance of one kind of infrastructure system often requires coordination with other infrastructure systems. Smooth operation of highways, for example may require development of drainage and flood management systems. Not only are there opportunity costs to sinking large investments in complementary infrastructure systems, but such investments can cause irreversible environmental degradation – in addition to degradation caused by putting the primary system in place. Developing complementary infrastructure systems can also lead to technology lock-in (Arthur 1989), and the associated phenomenon of carbon lock-in (Unruh 2000). With few exceptions, urban transport systems around the world are directly or indirectly fossil-fuel based. The ease and reliability of movement that they guarantee have spawned suburbanization in much of the Western hemisphere, and have fostered an increase in private car ownership, use of buses and rail. With the enlarged role of these systems in modern day-to-day life, institutions have developed to manage these systems and to meet the needs of their constituents, and as a result have further locked in the existing infrastructure. As a consequence, institutional development in the past often has added to the inertia that makes adaptive management of infrastructure systems difficult in light of changing environmental conditions or technologies (Unruh 2002).

2.2.4 Risk, Uncertainty and Surprise in Planning and Management of Infrastructure Systems

Since infrastructure systems typically have long life spans, their presence reflects knowledge and perceptions that decision makers have about the physical, biological and economic environment, as well as their expectations for the future. Capacity and design criteria for infrastructure systems typically are based on historic observations and extrapolations into the future. Planners ask themselves: What will be the size and income of the population over the next 20 years? What will be the rate of car ownership and travel demand? What are likely changes in land use, industrial, and residential location? How rapidly will relative employment and output shift among sectors of the economy? Answers to such questions are found on the basis of economic and planning models, most of which base their projections on an analysis of historic data. Safety margins are introduced into the projections to deal with risk and uncertainty. Yet, since planners and decision makers deal with socioeconomic systems that co-evolve in close relationship with other socioeconomic systems and their environment, there is ample room for surprises to occur and for projections to fail. For example, few investments in sea and airports, tunnels, and roadways reflect the impacts that climate change may have on sea level rise or increased adverse weather conditions, and therefore a need for better drainage and flood management. Current investments in transport infrastructure may also be misplaced if telecommuting and internet commerce gain in economic importance – those investments are too high if the advent of new communication technology leads to a reduction in transport demand; too low or geographically misplaced if new communication technology boosts economic activity and requires increased (long-distance) transport of goods, services, and people (Golob and Regan 2001).

The size of capital requirements, long lifetimes, pivotal role in socioeconomic development, and environmental impacts of infrastructure require institutions to take the long view. At times of rapid change in population size, economic activity or technology, traditional methods of forecasting future demands for infrastructure systems and services on the basis of past trends is likely to be inadequate. By the same token, a host of large-scale, long-term drivers such as climate change require that current design criteria are revisited, and that existing and new infrastructure is (re-)built to withstand, for example, higher wind, heavier snow and ice loads, higher surface temperatures, increased drought and precipitation, or elevated sea levels. As infrastructures adjust, volumes and patterns of material and energy use in urban areas (and their surroundings) change.

2.3 Changes in Urban Metabolism

Urban metabolism can be understood as the total flow of materials, energy and information into and out of an urban system (akin to our bodies' circulatory system) in order to generate goods and services (physical output), as well as increases in human well-being (non-material or social output) (Newcombe et al. 1978, Huang and Hsu 2003, Warren-Rhodes and Koenig 2001). Studies of urban metabolism measure inputs, outputs, and material recycling within a city or metropolitan area, often paying particular attention to the embodied energy (emergy) of goods, activities, and physical structures (Huang and Hsu 2003). The conversion of diverse physical quantities into units of energy allows for consistent comparison between cities.

By some accounts, urban metabolism can also be understood more explicitly in terms of sustainability. Mitchell (1998) defines urban metabolism as the “social as well as biophysical [means] by which cities acquire or lose the capacity for sustainability in the face of diverse and competing problems.” By sustainability he means the maintenance of resources and quality of life in the face of hazards and risk. This conception of urban metabolism aligns with the “ecological footprint” concept, often an integral part of any limits to growth argument. According to Wackernagel et al. (1999), “[t]he ecological footprint represents the critical natural capital requirements of a defined economy or population in terms of the corresponding biologically productive areas.” These biologically productive areas are taken to mean the amount of land available to create the low entropy (highly useful) energy needed to sustain consumption (production plus imports, minus exports) patterns of a given human population, as well as the land capacity needed to assimilate waste products and greenhouse gas emissions (Wackernagel et al. 1999, Wackernagel et al. 2000). The ecological footprint, as a relatively abstract idea, does not require specific information on the location of resources. It offers a common unit for analysis of consumption patterns, and may thus serve as a complement to energy-based assessments of urban metabolism.

At the scale of a city or region, most of the biologically productive land will be found outside of the system. This realization illuminates the ability of wealthy nations to externalize the effects of higher levels of consumption by both importing resources and exporting wastes, often over tremendous distances. A number of studies have been done calculating municipal ecological footprints, and the Global Footprint Network produces national ecological footprints, a summary of which is presented in Table 2. These national studies also calculate "biocapacity", the amount of productive land each nation has at its disposal, in order to relate consumption to natural resource endowment. On the whole, human society is consuming more materials and energy than is globally available over the long-term, shown as an overall global "ecological deficit".

Locally, cities are also consuming more than is regionally or globally available over the long-term. A study of York, UK calculated the total ecological footprint of the city to be 1,254,000 ha, yielding an average per capita figure of 6.98 ha (Barrett et al. 2002). This is not only significantly larger than the total land area of York, but is higher than the 5.6 ha per capita ecological footprint for the UK and developed nations as a whole, calculated in 2002 (European Environment Agency and Global Footprint Network 2005). Just under half of the total amount of materials consumed actually entered the city; the remainder accounted for the production and transportation of goods as well as other hidden energy flows and losses. A second regional study, of the Isle of Wight found total material consumption to be in excess of 750,000 tonnes (5.8 tonnes per capita) in 1998–99 (Best Foot Forward 2000). This consumption resulted in an ecological footprint of 5.15 ha per capita, the majority belonging to the tourist population visiting the region each year.

In general, urbanization increases energy demand as the needs of physical and social infrastructure grows within cities (Huang and Chen 2005). Much of this increased energy demand has been met with, and indeed facilitated by, the use of fossil fuels (Smil 1994, Unruh 2000). The relations between fossil fuel use and overall urban metabolisms is most notable in rapidly developing and urbanizing economies, such as the Democratic Republic of Korea (UNEP 2003) and India (UNEP 2001a), where per capita fossil fuel use across all sectors has increased rapidly over the last decade. A study by Warren-Rhodes and Koenig (2001) of the city of Hong Kong showed significant increases in both consumption and waste outputs between 1970 and 1997. The first urban metabolism study conducted on a North American region was completed in Toronto in 2003, suggesting slow development of the concept (Sahely 2003). This study showed that, in general, inputs (consumption) were increasing more rapidly than outputs (waste). Observed residential solid waste and wastewater outflows decreased in real terms over the study period (1987–1999).

The degree to which an urban area makes responsible use of its regional natural resources – both for the creation of material goods and the assimilation of waste products – has a significant influence on local environmental quality and quality of life. These effects are felt differently within and across countries, as well as across socioeconomic gradients, a topic explored in the next section.

2.4 Environmental Quality and Quality of Life

Urbanization means increasing rates of direct and indirect consumption of energy, materials, and ecosystem services, as well as significant displacement of natural ecosystems (McGranahan and Marcotullio 2006). Urban environmental problems, founded upon this appropriation and degradation of natural ecosystem structure and function, as well as stress on social institutions and urban infrastructure, vary regionally and through time as cities develop economically; a number of researchers (eg. McGranahan et al. 2001) have supplied graphic representations of this phenomenon. As can be seen in Figure 1, local environmental concerns, such as indoor air quality and sanitation, are much more pronounced in rural and low-income urban conditions. These problems are largely driven by development paths characterized by rapid demographic change that do not significantly account for key biological and ecological processes, such as the dynamics of infectious diseases and the provision of ecosystem services. Regional problems, such as declining outdoor air quality, emerge as cities develop and incomes increase. Industrialization and the increased use of private automobiles, characteristic of a development path in larger cities that fails to consider effects on regional ecosystems, are indirect drivers of these problems. More global problems, such as climate change, increase with increasing development and wealth. Excessive material wealth, exaggerated ecological footprints, generation of greenhouse gas emissions and solid waste, and a development path ignorant of (or unconcerned with) global effects of consumption are driving these changes. The time scale over which these concerns are experienced also changes, more local concerns posing much more immediate threats to health and well-being, global problems occurring slowly, damage being harder to see, understand and react to. Some of the most serious conditions at present are due to rapid urbanization that is causing more local and immediate environmental health issues (i.e. inadequate sanitation and access to clean drinking water) to be experienced at the same time as more modern, global concerns (i.e. climate change), effectively reducing cities' capacity to respond to all problems.

3. Urban Regional Assessments

Recognition of the complexity of urban change – environmental, economic, and social – has spawned research programs to improve knowledge about complexity and to use that improved knowledge as an input into policy and investment decision making. Two related strands of research are discussed here. The first concentrates on monitoring and understanding biophysical processes and associated technological change, the second more readily addresses the interdependencies of environmental and socioeconomic change in cities.

3.1 Environmental and Technical Change in Cities

Among the first efforts to advance understanding of complex environmental processes from a basic science perspective in the U.S.A. are the Long Term

Ecological Research (LTER) programs established by the U.S. National Science Foundation. The LTER programs, established in 1980, support interdisciplinary research at 26 sites across the United States. Research projects investigate ecological processes – and in the case of the two urban LTER sites (Central Arizona–Phoenix and Baltimore, Maryland), social-ecological interactions – over large temporal and spatial scales. There are five "core areas" on which each LTER site focuses: primary productivity, populations, movement of organic and inorganic matter, and disturbance patterns (Long Term Ecological Research Network 2006). Major results from the LTER research projects include support for the link between biodiversity and large scale ecosystem disturbance (i.e. climate extremes associated with global climate change) and insights into the relationship between urbanization and desertification, particularly in the U.S. Southwest (Pehr 2006).

The two urban LTER sites recognize the fundamental importance of humans in urban landscapes and seek to place humans within the context of larger ecosystems, recognizing their relations to local natural systems. The urban LTER sites are being carried out in geographically, hydrologically, socially, and economically distinct places. Phoenix is a relatively young city on the rise, characterized by high quality of life but also significant water stress. Baltimore, on the other hand, is well known for its degraded infrastructure, crime and population decline. Its major environmental concerns include water pollution of the Chesapeake Bay. Accompanying programs by the U.S. National Science Foundation include, for example, initiatives to "Improve Urban Interactions", which focuses on new tools for urban research in interdisciplinary settings (e.g. NSF 1997). Similar and related research programs are also being promoted in Europe such as in the EU Fifth Framework Program on the “Cities of Tomorrow” (EC 2006) and the International Human Dimensions Program on Global Environmental Change (IHDP) on “Cities and Industrial Transformation” (IHDP 2001).

3.2 Integrated Urban Assessment of Global Change Impacts

Significantly younger than the LTER sites, and less formally connected, are a host of current urban assessment projects that were spawned by the recognition that global environmental change influences urban dynamics. The resulting impacts on cities and possible response options hitherto were neglected in research, policy, and investment decision making. These projects have paid special attention to the influences of climatic change on the adequacy and reliability of urban infrastructures, associated changes in urban environmental quality and quality of life. In many instances, the underlying conceptual framework for analysis is some variant of the “drivers-pressure-state-impacts-response” (DPSIR) approach proposed by the OECD (1993) and widely used by the European Environmental Agency (1998) and other institutions. In its basic form it distinguishes environmental, economic, and social components of the (urban) system, sometimes with a refined representation of individual infrastructure elements and their relationship to each other and to the overarching socioeconomic and environmental system as shown in the larger rectangle of Figure 2.

Integrated urban assessments, for each selected system element, describe its state, identify impacts on the respective element, and determine the responses of system elements to impacts. For example, water treatment infrastructure may be characterized by treatment capacities and capacity utilization. Impacts on those state variables may come from changes in population, economic activity, technology, or rainfall and runoff. Responses may be in the form of system failure, retrofits, upgrades, or changes in technology or demand elsewhere in the larger system. In many instances, changes in one element of the system (water treatment) may trigger changes elsewhere (e.g. energy supply for water treatment), thus creating ripple effects with often time-lagged, non-linear relationships to the original stimulus for change.

Indicators for element-specific and integrated (system-wide) impacts are quantified to inform investment and policy choices, which in turn feed back as new impacts to influence system states. To some extent, system changes are related (or, at least in principle, relatable) to the metabolism and overall macrobehaviors and emergent properties of the city. The latter are the subject of the next section of this paper.

Examples of more narrow assessments of global change impacts on cities – without explicit accounting for material and energy flows and without explicit efforts to provide a complex systems perspective to the emergent behaviors – are presented in Table 3. This table suggests that more recently, urban integrated assessments generally have become more ambitious with respect to the number of infrastructure systems and interactions they analyze, the diversity and roles of stakeholders in the respective projects, and the diversity and sophistication of methods and tools used to carry out the research. Still somewhat relegated to the sidelines are the actual social dynamics that accompany urban impacts and adaptations to climate change. This is largely true for the urban LTER projects discussed above.

Examples of larger-scale analyses that cover a mix of rural and urban areas and explicitly deal with underlying social issues include the work by Hollman et al. (2005a, b) for East Anglia and Northwest England. However, there, in part to be able to deal with a larger area and to include social dynamics, the resolution with respect to individual system components (infrastructures, economic sectors, etc.) remains relatively low, compared to the narrower, urban region-focused studies presented in Table 3.

Despite the advances in modeling and analysis of complex urban dynamics brought about by all of these studies, the field of integrated urban impact assessment is young and remains fairly disconnected from, for example, basic science approaches as illustrated in the urban LTER projects and similar efforts around the world. At the same time, insights from complexity theory have only implicitly guided the design of these studies and the interpretation of results.

4. Understanding the Complexity of Urban Systems

Traditionally, city planning has focused on spatial planning, housing, transport, energy, and water systems to individually and specifically address the drivers of urban change discussed in Section 2 above. As the interrelations among individual drivers are becoming increasingly apparent, focus has shifted to integration of planning and management of land use with physical infrastructure, sociocultural and economic issues, as well as environmental quality. In the process, insights from complexity theory have been proposed as relevant to understand and guide the development of cities. Those insights are used in two different, though related ways.

First, there is the study of cities as complex systems, where the macrobehaviors of cities are modeled and investigated much like the macrobehaviors of chemical or biological systems. The relevant modern conceptualizations of complexity used in this research originate in the works of Illia Prigogine and his co-workers (see, e.g., Prigogine 1980), who have studied open systems – typically physical or chemical systems that were characterized by the exchange of mass and energy across system boundaries. Here, non-equilibrium thermodynamics provided crucial insights into the behavior of many such systems. As these systems are exposed to changes in energy flows from the outside, structures emerge inside that help dissipate those flows. When stability thresholds are exceeded, the systems may experience a transition to a new structure which, in turn, possesses its own limited development potential (Nicolis and Prigogine 1977).

The early work on silicones and other materials was soon extended to address the formation of and change in the structure of biological systems, from cells to entire ecosystems (Prigogine et al. 1972). For example, Eric Schneider (1988, p. 116) described "life itself [a]s a product of the thermodynamic histories of the global ecosystem as it evolved from chemical elements and, through energy flux transformations, developed useful genetic materials that reproduce and metabolize into highly organized systems through stepwise energy transformations."

The appeal of complexity theory as a unifying framework to explain system change was further extended, at least by analogy, to shed light on economic growth and development (for a review see Ruth 2005). Some have begun to build computer simulation models of social and economic systems which describe them explicitly as non-linear, open, self-organizing systems. Peter Allen (1997), a former student of Prigogine's, has been among the first to do so for urban systems. The urban dynamics simulation models of Jay Forrester (1969), though not explicitly guided by complexity theory, do recognize the importance of system openness, non-linearities and time lags. His models focus on the interplay of physical urban infrastructure, economic development, and pollution in a way that is closely related to the notion of urban metabolism discussed above.

While much of the work on complex systems behavior has been descriptive or simulation oriented, lessons from complex systems analysis are slowly beginning to inform policy and investment decision making. If systems, such as cities, are indeed best described as open, diverse in structure, and varied in interacting components; if furthermore, many of these interactions are non-linear and time-lagged; and if the components themselves are complex systems nested within other complex systems, then – so the argument goes – a complex systems approach is needed to understand and guide their behavior (Rotmans and van Asselt 2000, Rotmans 2006). Complex systems analysis, thus, has rapidly evolved from a descriptive into a prescriptive endeavor. In doing so, it has encountered inherent challenges when trying to provide “management advice” on the basis of a world view that emphasizes non-deterministic system behavior.

As a consequence of complexity, novelty and surprise are unavoidable features of system development (Funtowicz and Ravetz 1991). One approach to dealing with complexity and uncertainty in a pragmatic fashion is to require that different perspectives on the various system elements and their interactions are provided by different stakeholders from a range of scientific, public, private, and non-profit communities (Bond 1998, Hulme and Taylor 2000). Several of the integrated urban assessments discussed above have attempted to provide a rich, multidisciplinary perspective, informed – and on occasion guided – by insights from many different stakeholders. Yet, managing the contributions from a large and diverse set of stakeholders has itself become a complex management task. The scarcity of resources for those projects and their inherent short duration of usually only one to five years have largely prevented them from becoming institutionalized to a point where they can have any long-reaching policy impact. As a consequence, the extent of stakeholder dialog and involvement is frequently curtailed to keep projects within resource constraints.

A second means of capturing a wide range of influences on the behavior of urban systems it to craft scenarios that are consistent both internally and broadly with respect to the contributed viewpoints on the strength and role of outside influences on the system and drivers within the system. Frequently, contrasting scenarios represent alternate viewpoints of stakeholders. Playing those scenarios out – often with the help of computer models – and interpreting their consequences across sectors and across time can provide valuable input for institutional learning. Furthermore, to the extent that the primary elements of an urban system are formally modeled, the quantitative (and qualitative) outputs from simulation exercises can be used to inform feedbacks between system response and intervention through investment and policy choice, as already indicated in Figure 2 above.

Computer models of complex urban dynamics can improve, iteratively, the knowledge of stakeholders, and with that knowledge perhaps improve decision makers' ability to influence those dynamics. It is in this sense that adaptive management (Holling 1978, Gunderson et al. 1995) can be a key element in problem solving. However, an added challenge in urban planning and management that is not present in many of the other areas to which adaptive management has been applied, lies in the lumpiness and irreversibility of infrastructure investments. Long lead times and life times of projects in many ways prevent adaptation – once an urban highway system is put in place or an underground sewer network has been laid, changes are virtually impossible. Here it becomes even more important to explore, in structured and quantifiable ways, the potential future implications of current investment and policy choices. Implementing more anticipatory management (Ruth 2006b) is proving to be even more of a challenge than establishing adaptive management as a guiding principle for investment and policy making.

5. Summary and Conclusions

In this paper we reflected on the drivers of urban change, and various approaches to understand and manage that change. While the research areas in urban theory and analysis are broad, we have deliberately focused on recent developments that were spawned by, or are otherwise closely related to, insights from complexity theory, and that are part of the ongoing discussion about the impacts of global (environmental) change on quality of life in cities. We have argued that continued urbanization, more extensive globalization, and increasing impacts of global environmental change pose complex challenges to urban planners and managers and require that the scientific community develops and uses concepts and methods that advance the understanding of that complexity. This is particularly important if the science is used to inform policy and investment decision making.

Yet, as urban analysis begins to integrate insights about the complex behavior of urban systems and uses frameworks for analysis, either explicitly or implicitly, that are informed by complexity theory, several challenges emerge. First, there is the problem of mismatched world views: decision makers are asking for projections on which to base their decisions; integrated assessments provide diverse scenarios of potential future system trajectories. Rather than basing decisions on projections, the challenge will be to identify strategies that are robust for a wide range of possible scenarios. Second, and closely related to the first of these challenges: for one group, models and reports are an end product that (linearly) enters into a decision making process. For the other, integrated assessment is part of an iterative process of adaptive and anticipatory management. Given limited budgets and planning horizons, adaptive and anticipatory management are difficult to implement in many institutional settings.

Efforts to overcome these challenges are themselves rife with problems. Embracing broad stakeholder communities in the scientific process can bias the science through undue influence of special interests. It can also reduce the value that science adds to the decision making process if it has to meet some lower common denominator during the consensus building process, for example if only a narrow set of scenarios are presented to scope investment and policy choices, or if the creation of scenarios itself is strongly biased towards pre-existing notions of what the future *will* look like. Current environmental research points as much to the complexity of the decision making process itself, as it contributes to the understanding of complex relationships among urban infrastructure, population and institutions. The biggest challenge may well lie in the innovation of institutions that plan for, and manage urban dynamics.

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Table 1: Total and urban population trends by level of development and income, 1975–2015

	1975		**2001**		**1975-2001**		**2015**		**2001-2015**	
	Total (millions)	**Urban (%)**	**Total (millions)**	**Urban (%)**	**Total (% Δ)**	**Urban (% Δ)**	**Total (millions)**	**Urban (%)**	**Total (% Δ)**	**Urban (% Δ)**
High HDI	972.3	**71.7**	1,193.9	**78.3**	0.8	*9.2%*	1,282.0	**81.5**	0.5	*4.1%*
Medium HDI	**2,678.4**	28.1	**4,116.2**	41.6	1.7	*48.0%*	**4,759.1**	49.4	1.0	*18.8%*
Low HDI	354.5	19.1	737.5	31.6	**2.8**	***65.5%***	1,021.6	39.7	**2.3**	***25.6%***
High income	782.0	**73.8**	935.9	**79.4**	0.7	*7.6%*	997.7	82.6	0.5	*4.0%*
Middle income	**1,847.5**	35.0	**2,694.8**	51.6	1.5	***47.4%***	3,027.9	60.7	0.8	*17.6%*
Low income	1,437.1	22.1	2,515.0	31.5	**2.2**	*42.5%*	**3,169.0**	38.1	**1.7**	***21.0%***
World	4,068.1	37.9	6,148.1	47.7	**1.6**	*25.9%*	7,197.2	53.7	**1.1**	*12.6%*

Source: UNDP 2003

Table 2: Ecological Footprint and Biocapacity, 2002 data

	Population (millions)	**Total Ecological Footprint** (global ha/person)	**Food, fiber, and timber Footprint** (global ha/person)	**Energy Footprint** (global ha/person)	**Total Biocapacity** (global ha/person)	**Ecological Deficit or Reserve** (global ha/person)
WORLD	6,225.0	2.2	0.9	1.2	1.8	-0.4
High income countries	925.6	6.4	2.1	4.1	3.4	-3.0
Middle income countries	2,989.4	1.9	0.9	0.9	2.1	0.2
Low income countries	2,279.8	0.8	0.5	0.3	0.7	-0.1

Source: European Environment Agency and Global Footprint Network (2005)

Table 3: Integrated Assessments of Climate Impacts and Adaptation in Urban Areas

	Bloomfield et al. (1999)	**Koteen et al. (2001)**	**Rosenzweig et al. (2000)**	**Kirshen et al. (2004)**	**Hoo and Sumitani (2005)**	**Jollands et al. (2005, 2006)**	**Lange and Garrelts (2006)**
Location	Greater Los Angeles, California, U.S.A	New York, New York, U.S.A	Metropolitan New York, New York, U.S.A	Metropolitan Boston, Massachusetts, U.S.A	Metropolitan Seattle, Washington, U.S.A	Hamilton and Wellington New Zealand	Hamburg and Bremen, Germany
Coverage:							
Water Supply	X	X	X	X		X	X
Water Quality				X		X	X
Water Demand				X		X	X
Sea-level Rise	X		X	X	X		X
Transportation				X	X	X	X
Communication							X
Energy			X	X		X	
Public Health							
Vector-borne Diseases							
Food-borne Diseases	X						
Temperature-related Mortality							
Temperature-related Morbidity	X	X		X		X	
Air-quality Related Mortality						X	
Air-quality related Morbidity			X			X	
Other	X	X	X			X	X
Ecosystems							
Wetlands							
Other (Wildfires)	X		X				
Urban Forests (Trees and Vegetation)		X			X		
Air Quality		X				X	

Table 3: Continued

	Bloomfield et al. (1999)	**Koteen et al. (2001)**	**Rosenzweig et al. (2000)**	**Kirshen et al. (2004)**	**Hoo and Sumitani (2005)**	**Jollands et al. (2005, 2006)**	**Lange and Garrelts (2006)**
Extent of:							
Quantitative Analysis	Low	Medium	Medium	High	Low	High	Medium
Computer-based Modeling	None	Low	Low	High	None	Medium	None
Scenario Analysis	None	None	Medium	High	Medium	Medium	Medium
Explicit Risk Analysis	None	None	None	None	None	Medium	High
Involvement of:							
Local Planning Agencies	None	None	High	High	High	High	High
Local Government Agencies	None	None	High	High	High	High	High
Private Industry	None	None	None	Low	None	None	Low
Non-profits	None	None	Low	High	None	None	Medium
Citizens	None	None	None	Medium	None	None	Low
Identification of:							
Adaptation Options	X	X	X	X	X	X	X
Adaptation Cost			X	X		X	
Extent of Integration Across Systems	None	None	Low	Medium	Low	High	Low

Figure 1: Evolution of urban environmental problems (after McGranahan et al 2001)

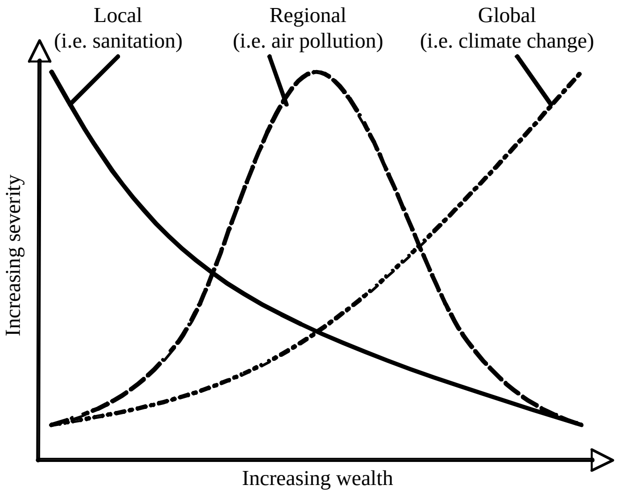
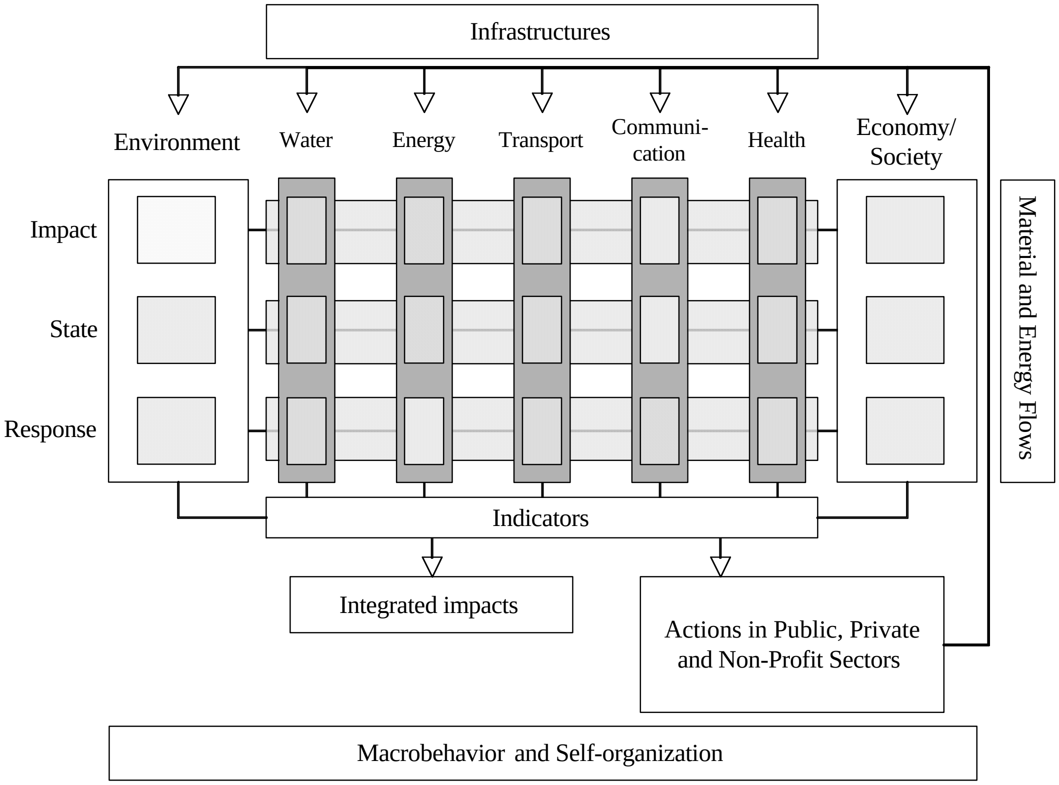


Figure 2. Integrated Urban Impact Assessment Framework



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