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Urban ecology and industrial ecology

Xuemei Bai and Heinz Schandl

Introduction

Industrial ecology and urban ecology are distinct disciplines with different professional communities, but they share many common concepts and approaches. This chapter explores the ways industrial and urban systems and the science relating to them interact, through reviewing the history and main areas of research within each discipline, common and distinctive approaches, cross contributions, and emerging frontiers. Material and energy flow analysis, which is a common approach in both industrial and urban ecology, is used as an example to articulate linkages between the disciplines. While they have different starting points and remain as separate disciplines, there is also a merging and coevolving trend in research scope and methodology in urban ecology and industrial ecology, with industrial ecology extending its scope to include literature dealing with social and management dimensions, and an increasing volume of literature addressing production and consumption subsystems within cities appearing in urban ecology.

Industrial and urban ecosystem

There are strong spatial and functional linkages between cities and industries. Many industries are located in or nearby cities, taking advantage of the concentration of labour and infrastructure provided by urban agglomerations. Conversely cities rely on industrial activities, whether manufacturing or services, to maintain their economic vitality and competitiveness. These spatial and functional linkages often result in strong environmental linkages too, with the environmental performance of industries within cities affecting the environmental quality of cities and the livelihoods and well-being of urban dwellers, and cities sometimes making strategic decisions around the development or relocation of particular polluting industries (Bai 2002). The nature and complexity of the relationship between the industrial system and the urban system can vary due to functional differences between cities, their stages of economic development, external factors such as globalization, and the institutional and governance settings within which they operate.

Both urban and industrial ecology have drawn parallels between cities and ecosystems, and industries and ecosystems. While urban ecology has used the ecological metaphor to reflect the
complexity that occurs within an urban system, industrial ecology has mainly tried to model industrial processes as an analogy for biological processes. An industrial system located in a city can be considered as a nested subsystem within an urban ecosystem (Ma and Wang 1984), with complex interactions between the city and the subsystem often regulated at a higher level by the urban ecosystem (Kaye et al. 2006; Bai 2007). From an ecosystem point of view, both the industrial system and the urban are viewed as open systems that import low entropy energy and raw materials from their surroundings and export high entropy energy, products and waste beyond their system boundaries to sustain their function. These metabolic interactions provide one foundation for the methodological similarities among the two disciplines of industrial ecology and urban ecology.

**A brief history of industrial ecology and urban ecology**

Industrial ecology aims to model industrial systems to operate like biological systems. In ecological systems, the wastes produced by one species tend to be a resource for another species. By the same token, industrial ecology designs clusters where the output that one industry considers to be waste can be used as a valuable input, i.e. raw material for another industry, thus reducing the use of raw materials, pollution and saving on waste treatment (Frosch and Gallopoulos 1989; Levine 2003).

Industrial ecology is a relatively new discipline. Seminal research such as Ayres and Kneese (1969), the *Limits to Growth* report by the Club of Rome (Meadows et al. 1972), as well as Commoner (1971), set the scene for a new interdisciplinary research field linking natural scientists, physicists and engineers with planners and social scientists to look at the interface between industrial and environmental systems, the material and energy flows that enable production and consumption activities and the potential for improving the effectiveness and efficiency of resource use by mimicking ecological processes, such as closing the loop by reuse and recycling.

While precursors existed in the late 1960s and early 1970s, a new research community was formed in the late 1990s under the banner of industrial ecology.

Urban ecology, in contrast, has evolved over a much longer time frame. Some of the earliest research efforts that can be classified as urban ecology were made by the Chicago School of Sociology, which applied ecological concepts to study the patterns and dynamics of cities. For example, Park et al. (1925) borrowed the concept of succession from plant ecology for describing land use change in cities. Odum (1975; Odum and Odum 1980) described cities as open systems, which establish a metabolic interaction with their environment. Wolman (1965) conducted the first metabolism analysis for an imaginary city of one million, estimating the total input and output of various energy, materials and waste streams. The first metabolism analyses in real world cities were conducted under the UNESCO Man and the Biosphere (MAB) Program during the 1970s and 1980s (Boyden et al. 1981).

Many urban ecologists have focused on studying the natural components of cities, i.e. the flora and fauna within cities (Sukopp and Werner 1982; Sukopp 1998), which is referred to as “ecology in cities”. While this remains an important part of urban ecology, especially in the application of urban and landscape planning and design, recent studies have focused increasingly on the “ecology of cities” (Grimm et al. 2000; Grimm et al. 2008). This more fundamental approach treats cities as distinctive ecological systems and studies their patterns, processes, functions and dynamics. In this research tradition, cities are conceptualized as coupled social-ecological systems which are complex, adaptive, dynamic and constantly changing, with their overall performance and trajectories shaped by both internal and external factors (Ma and Wang 1984; Alberti et al. 2003; Bai 2003; Alberti 2008; Ernstson et al. 2008).


Current scope of interests

According to Graedel and Allenby (2002), research questions in industrial ecology usually fall under four major domains.

The first research domain looks at industrial systems and their potential for improvements in resource use and emissions intensity when modelled after ecological systems. Research in this area has looked at the potential for linking industrial sectors to allow for synergies and to establish cycles for materials that are used in industrial processes. The aim of this research has been to moderate resource use and environmental impacts through technological improvements and product design.

The second domain has looked at resource use in socio-economic systems at various functional and geographic scales to empirically assess the magnitude of resource use and emissions, in order to improve the management of society-environment interactions through informed environmental management at national, sectoral and corporate levels.

The third research domain has investigated the future of technology-environment relations by employing scenario analysis techniques for the development of future technology and its relationship to the environment, to better understand how changes in environmental systems affect technological systems.

The fourth research domain has looked at how to operationally define and address sustainability, and how to measure it.

Research has been guided by a number of quite influential theoretical concepts or notions including industrial metabolism, industrial symbiosis and life cycle approaches, which have become associated with neighbouring research fields such as ecological economics. Most of the research has had a strong empirical basis and evolved around a family of methodological tools including material and energy flow analysis, substance flow analysis, life cycle assessment, ecological footprint assessment, input-output analysis and design for the environment. Much of the research has focused on industry or policy impact with regard to redesigning industrial processes, industrial design and improving firm based standards, or through informing policy planning and programmes, and evaluating past policies.

Interest in urban research in the industrial ecology research community has grown since 2000, examining regional and global impacts of cities through industrial ecology tools, sustainable production and consumption, and research on urban metabolism and how urban form, density, transportation and design choices affect these flows.

It is difficult to produce a handful of key questions in urban ecology, given its diversity and interdisciplinary nature. However, three main domains of interest can be identified from the scholarly literature:

Ecology in cities

This research domain deals with the natural component of cities, studying ecological structure and the functioning of habitats or organisms within cities. This research domain has the longest history in urban ecology, and remains an important part of urban studies. In addition to traditional vegetation, flora and fauna studies in cities (Zipperer et al. 1997; Sukopp 1998), there has been increasing interest in looking at the urban physical environment as affected by human activities (Douglas 1983), e.g. urban heat islands and anthropogenic energy use (Oke 1995), and urban hydrological modification (Paul and Meyer 2001); as well as the ecological functions and services provided by the natural component of cities, e.g. urban green space and its role in mitigating the heat island effect (Wong and Yu 2005), and the role of nature in human health and wellbeing (Tzoulas et al. 2007).

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Human dimensions in cities

While traditionally ecologists have viewed human influence in an ecosystem as a “disturbance”, it is increasingly recognized that the structure and function of the Earth’s ecosystems cannot be understood without accounting for the dominant influence of human activities in ecosystems (Vitousek et al. 1997; Redman 1999). This is especially valid in an urban setting, where social activities are dominant, and drive ecosystem function and change. Grimm et al. (2000) suggest a conceptual framework to address three fundamental drivers underlying human action: flows of information and knowledge; incorporation of culturally based attitudes, values and perceptions; and creation and maintenance of institutions and organizations. Based on this framework, core topics for investigation include: demographic patterns, economic systems, power hierarchies, land use and land management, and environmental design (Redman 1999). Modern studies linking consumption behaviour to social psychology may also fall into this category (Jackson 2005).

Ecology of cities

This third strand of research views cities as coupled social-ecological systems, which include humans living in cities and urbanized landscapes (Alberti 2008). This approach examines entire cities or metropolitan areas from an ecological perspective, including biogeochemical cycles, material and energy flows, ecosystem patterns and processes, which collectively are referred to as the ecology of cities (Grimm et al. 2000). This research approach recognizes close linkages and multiple interactions among different components of the system, which in turn generates opportunities for realizing co-benefits, but also creates the risk of unintended consequences and trade-offs (Bai et al. forthcoming).

Urban metabolism as linking and/or common approach

One of the most obvious common concepts shared between the industrial ecology and urban ecology communities is the notion of “metabolism”. Ayres and Simonis introduced the notion of industrial metabolism in their 1994 book which has since been used to guide research within the industrial ecology research community and has led to applications at various functional and geographic scales, including national economies, economic sectors, businesses, products, regions and cities. The vibrant research activity and the close links which could be established to policy and multilateral institutions such as, for instance, the Organization of Economic Cooperation and Development (OECD) or the United Nations Environment Program (UNEP) enabled standardization and harmonization of methodologies most successfully at a national scale, but with implications for research at other levels such as cities. In 2007, the OECD in collaboration with the European Statistical Office (EUROSTAT) released a methods guidebook for national material flow accounts. This guidebook has set a standard for application of metabolism research and accounting for material and energy flows at urban scales (EUROSTAT 2007).

Fischer-Kowalski (1998) further elaborated the metabolism concept, focusing on the interface between society and nature in terms of the exchange of materials and energy. According to Fischer-Kowalski’s seminal overview of the origins of the social metabolism concept, the theory looks back on a long history in a number of scientific disciplines such as sociology, human geography, cultural and ecological anthropology and economics starting around 1860 (Fischer-Kowalski 1998). The metabolism concept describes labour as a process between humans (society) and nature in which society organizes and satisfies its material demands. It is within the labour process, and through the application of technologies, that socio-economic systems organize
essential supplies of materials and energy for production and reproduction of human societies (Schandl and Schulz 2002). The metabolism approach views social systems as analogous to ecosystems with regard to their fundamental requirement to organize and maintain a throughput of materials, water and energy which are extracted from natural sources, transformed in economic activities, used to build up stocks of buildings, vehicles and capital and consumer goods and ultimately disposed of into the environment in the form of waste and emissions via different paths (including water, air and land).

The social metabolism approach is based on a broader understanding of structurally coupled social-ecological systems (Boyden 1987; Fischer-Kowalski and Weisz 1999). As Figure 3.1 shows, the built urban environment and people living in cities are at the interface of the urban cultural system and the urban natural environment. Urban stocks are established and maintained by a continuous throughput of materials and energy, which are channelled through socio-technical systems organizing the provision of housing, mobility, food, energy and water.

The way in which the society-nature interface is organized depends on urban culture and institutions, and the way in which the urban-political economy operates. The notion that culture is a system of communication which guides the design and investment decisions that play out in the built urban system and deliver a very specific urban life world is highly important in the approach suggested by Fischer-Kowalski and Weisz (1999) that we draw upon here.

Overall, the industrial ecology strand of metabolism analysis focuses mostly on production systems, and is often applied in the analysis of national scale, major economic sectors.

The application of the metabolism approach to cities also has historical precedents. Wolman was the first to introduce the notion of urban metabolism in his classic 1965 study (Wolman 1965). He calculated energy, water and materials throughput for a hypothetical city of one million inhabitants using national United States production and consumption data. The first application of urban metabolism to an actual city was done for the Belgian capital, Brussels, by Duvigneaud and Denaeyer-De Smet (1977). Their analysis of energy and water flows as well as air pollution found that the city of Brussels was depending on its hinterland for the supply of energy and water and did experience comparatively high rates of pollution. The city of Hong Kong has also been a focus of urban metabolism research because the city boundaries match with the state boundaries and hence economic statistics have been readily available. This has enabled a series of urban metabolism studies including Newcombe (1977) and Warren-Rhodes and Koenig (2001), and especially the work of Boyden et al. (1981) who aimed to integrate indicators for relative quality of life in the city with the urban metabolic analysis.

Figure 3.1 The urban social-ecological system.
Since the late 1990s, there has been increased effort in urban metabolism research, resulting in studies for various cities in the United States (Tarr 1996; Grove and Burch 1997; Kennedy 2002; Tarr 2002; Jenerette et al. 2006), Europe (Hendriks et al. 2000; Pauleit and Duhme 2000; Ravetz 2000; Barles 2009; Bramley et al. 2009; Niza et al. 2009) and urban metabolism studies for Santiago de Chile (Wackernagel 1998), Sydney (Newman 1999) and Taipei (Huang and Hsu 2003).

There is another body of literature examining the environmental impacts of urban metabolic flows beyond direct material and energy requirements. Ecological footprint analysis starts with resource flow accounting but reinterprets resource use in terms of the land that was required to produce the respective resources in the first place (Wackernagel and Rees 1995). Studies on the urban ecological footprint include Collins et al. (2006), Folke et al. (1997), Luck et al. (2001), White (2001), and Jenerette et al. (2006). In general their major findings coincide, indicating that in terms of the primary resources cities need to service their urban metabolism, urban areas show a significant and increasing ecological footprint through their interaction with regional and global resource flows. Examining the carbon footprint of cities, Kennedy et al. (2009) conclude that because of small physical territories and related high-density and consumption levels, emissions outside the administered territory, i.e. embedded or up-stream emissions tend to dominate the urban carbon footprint.

All of these research efforts are surrounding a major research topic, namely the regional and global impact of cities, via their dependence on resource flows from elsewhere and their increasing emissions, driven by the globalization of economic activity, the production and consumption of goods and services, and employment. Cities play a major role in global metabolism as centres of consumption. Whilst cities already appear as significant resource users and greenhouse gas emitters on a per-capita basis when direct flows are taken as the basis of accounting, their impacts need to be adjusted upwards when research considers the raw material equivalent of cities’ resource consumption. Recently the research methodology for embedded, up-stream flows has been advanced considerably by Munoz et al. (2009) who used an input-output economics approach to account for the raw material equivalents of trade in Brazil, Chile, Columbia, Ecuador and Mexico, showing the considerable waste and emission stream that remains in countries with large extractive or industrial activities. Lenzen and Peters (2009) using a similar methodological approach looked at the resource mobilization of urban consumption in Australia from a spatially explicit point of view. While the issue of embedded flows has increasingly become an important research topic in metabolism research most of the methodological development has focused on the scale of the national economy. Urban metabolism research has been complicated by a lack of data for urban system boundaries resulting in a severe limitation for case studies. This has hampered progress in methodological harmonization among urban metabolism studies and between urban and national metabolism studies.

A very important research question is which factors influence a city’s metabolism? Five major factors can be indentified.

1 Natural factors, including a city’s geographic location and the associated spatial and climatic features, or the natural resource endowment and geomorphology of the city. For example, colder cities tend to have more energy use for heating.

2 Functional role of the city, e.g. the type and intensity of major economic activities. Industrial cities tend to have larger metabolic flows than financial or political centres.

3 Income level also affects the type and amount of urban metabolism. With economic development, cities attract more consumer goods and discharge more greenhouse gases (Bai and Imura 2000; Warren-Rhodes and Koenig 2001; Bai 2003).
4 Urban policy and management practices have the potential to make a difference. Cities have also been identified as important sinks for strategic materials such as copper and iron, and the industrial ecology literature has looked at the potential for urban mining in comparison to consuming natural reserves of these resources (van Beers and Graedel 2007; Halada et al. 2009). There is potential for significant recycling and reuse of these materials within cities, which would reduce the overall inflow and outflow of resources. Some recent studies have started to explore spatially explicit representations of urban resource stocks and flows, in order to predict future construction waste flows and their potential use in urban infrastructure renewal (Tanikawa and Hashimoto 2009).

5 Urban planning and design choices. While, traditionally, urban metabolism studies have focused on total or per capita amounts, the importance of spatial distribution of building and infrastructure stocks is increasingly recognized, and spatial issues are known to affect transportation choice, building energy efficiency, etc. (Doherty et al. 2009; Newman and Kenworthy 2006).

**Common frontiers of industrial ecology and urban ecology**

Urban Ecology and Industrial Ecology have had many points of contact and cross influences over time, allowing for fruitful dialogue between the two neighbouring interdisciplinary research fields. In the light of growing concern about global environmental change and urban living, building more coherent linkages would seem appropriate. These linkages would best be built around the increasing recognition of the social and governance dimension both in research communities, and around the integration of complex system thinking into research (Korhonen et al. 2004). This would enable a stronger conceptual position and provide guidance for empirical studies aiming to inform urban policies that deal with the challenges of globalization and global environmental change.

In the current situation of continuing population growth, rapid urbanization and industrialization and the convergence of major resource use and global environmental issues (Raupach et al. 2007; Weisz and Schandl 2008; Schandl and West, forthcoming) there is an increasing research and policy focus on the transformability of urban structures to use less natural resources and energy and produce less waste and emissions. This poses a serious public policy issue and has led to the development of urban sustainability strategies in many cities around the world. Despite being well-intentioned, many strategies lack a solid baseline assessment of historical and current trends for resource use and impacts, and lack a comprehensive and conceptually sound basis. Policymakers may misunderstand the complexity of urban systems and thus arrive at policy conclusions which are simplistic and sometimes even counterproductive for achieving urban sustainability.

Industrial ecology started as the study of material and energy flows underpinning and resulting from socio-economic activities by looking at different scales (national, sectoral, businesses and firms, products) and cross-scale interactions. Based on the insights from metabolic analysis, the research has looked at ways and methodologies to close cycles in order to minimize the environmental impact of these activities. There has been a strong focus on design, engineering and technological innovation within industrial systems and a lesser focus on the analysis of institutional arrangements and related public policy questions.

The research field has, however, moved significantly towards integrating social sciences into the interdisciplinary endeavours to analyse and improve resource use and environmental impact of production and consumption across scales. Increasingly, the scholarly literature from neighbouring research fields such as economic sociology, institutional analysis and institutional
economics, as well as science and technology studies, has referred to industrial ecology research to reflect the social embeddedness of industrial ecology (Boons and Howard-Grenville 2009); see also Thomas et al. (2003) for a focus on policy.

Despite this growing interest in the social domain of industrial ecology, the urban metabolism concept already addresses the fact that society–nature interactions and related material and energy flows in a modern industrial society are organized and managed at the social level, well above the individual. Industrial societies have established structural coupling between society and resources via socio–technological systems for major areas of provision including water and sewerage, energy, housing, mobility and food. Each such system consists of institutional and infrastructural elements and mobilizes a bulk resource. These interactions tend to be complex or at least complicated, and show inertia towards change because of the stability of institutional arrangements and the long-term use of large infrastructure such as urban transport infrastructure, commercial and residential buildings, and water and sewerage infrastructure. Major improvements in socio–technological systems may occur through the improvement of existing systems and efficiency gains but often more fundamental change is required, such as has been envisaged by the systems innovation literature (Elzen and Wieczorek 2005; Geels 2005).

The urban ecology research community has also increasingly recognized the important roles of the social behaviour of citizens, and urban policy making and management decisions, in shaping and regulating linkages between cities and the regional and global environment (Bai et al. forthcoming). There have been attempts to extend the traditional urban metabolism approach beyond a resource flow perspective (Newman 1999; Newton and Bai 2008). Figure 3.2 builds on these attempts, and shows the input of natural, capital and information resources into a city, and the output of products, knowledge and services, waste and other emissions. Urban system structures and functions, which include the natural and built environments within cities, distribution of goods and provision of services, urban design and governance, and urban lifestyles and consumption activities, mobilize and shape the input and output. The performance of an

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**Urban system input**

- Natural resource (food, energy, water, other materials)
- Capital
- Information

**Urban systems structures and functions**

- Urban land and water
- Ecosystem services
- Urban infrastructure
- Distribution of goods
- Provision of urban services
- Industrial processes
- Urban planning
- Urban governance
- Urban life style

**Urban system outputs**

- Industrial products and services
- Knowledge
- Wastes and other emissions

**Urban Systems Performance Indicators**

- Social (e.g. employment, liveability, health and well-being, culture and heritage, equality)
- Economic (e.g. competitiveness, productivity)
- Environmental (e.g. air and water pollution level, noise level, resource efficiency, etc.)
- Governance (e.g. participation and inclusion)
- Environmental Health
- Culture and Heritage
- Air and Water Pollution Levels, Noise Levels, etc.

**Figure 3.2** Integrated urban metabolism and urban system performance indicators.
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Urban system can be measured by a set of indicators that includes social, economic, environmental and governance aspects, which can then be used to inform and guide policy.

The integration of social, economic and governance dimensions into urban and industrial ecology expands the boundary of the disciplines as well as adding complexity in terms of modelling and analysing them. This leads to another common frontier in both urban and industrial ecology, which is the increasing adoption of a complex systems view. Jonathan Spiegelman (2003) argues that together with non-equilibrium thermodynamics and the application of metabolism analysis in both urban ecology and industrial ecology, complexity theory has the potential to integrate anthropogenic and natural activities into one framework. Complex system science aims to describe and understand systems that are characterized by nonlinear behaviour, feedbacks, self-organization, irreducibility and emergent properties (Anderson 1972). Related theories such as systems dynamics, cellular automata, agent-based modelling, and network analysis have been applied to urban problems such as population, land use change and transportation modelling (Baynes 2009). Other recent applications have included a study of social interactions in cities and their implications, which concluded that these interactions follow a sublinear scale and are strong drivers of innovation, economic productivity, and the spread of disease (Bettencourt et al. 2007).

A future research programme drawing from the rich scholarly knowledge within both urban ecology and industrial ecology would be well placed to deal with major urban sustainability issues. Such research could investigate how linear flows of resources might be changed to a circular mode, where resources are recycled and reused within and among subsystems of cities. Research would look at the role of economic growth and industrial activities for urban metabolism, the increasingly important interface between urban governance and management and industrial activities; and how to model and analyse the complex interactions and feedbacks in an urban system. It would also explore how the resilience of cities, in terms of sustaining functions, can be maintained and enhanced to weather a changing climate and to deal with major social issues by understanding cities as complex adaptive systems (Pickett et al. 2004). There is a need for a dynamic perspective on urban metabolism and urban development, the modelling of urban metabolism in a spatially explicit way, and for a much better understanding of the interrelationship of urban forms and structures with urban metabolism. This needs to be accompanied by a sound conceptual and empirical analysis of the role of cities in national and global resource flows and emissions, and would involve the attribution of up-stream flows of resources and emissions to urban centres, as well as providing better understanding of the role of cities in decision making and the framing of a dominant production and consumption culture. Finally, an improved understanding, informed by social science, of the challenges involved in transforming urban structure and form by urban development strategies and planning policies will be essential to drive sustainable urban development.

References

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