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An integrated material metabolism model for stocks of urban road system in Beijing, China

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HIGHLIGHTS

- Massive materials flow from the lithosphere into cities and form infrastructures.
- A stock model based on bottom-up method was built for calculating accumulated materials.
- Nearly 80% of the total stocks were stored in roads and 20% in ancillary facilities.
- The construction of interchanges and arteries was excessively emphasized.
- Cross-sectional parameters of low-grade roads will largely impact stocks scale.

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ABSTRACT

Rapid urbanization has greatly altered the urban metabolism of material and energy. As a significant part of the infrastructure, urban roads are being rapidly developed worldwide. Quantitative analysis of metabolic processes on urban road systems, especially the scale, composition and spatial distribution of their stocks, could help to assess the resource appropriation and potential environmental impacts, as well as improve urban metabolism models. In this paper, an integrated model, which covered all types of roads, intersection structures and ancillary facilities, was built for calculating the material stocks of urban road systems. Based on a bottom-up method, the total stocks were disassembled into a number of stock parts rather than obtained by input–output data, which provided an approach promoting data availability and inner structure understanding. The combination with GIS enabled the model to tackle the complex structures of road networks and avoid double counting. In the case study of Beijing, the following results are shown: 1) The total stocks for the entire road system reached 159 million tons, of which nearly 80% was stored in roads, and 20% in ancillary facilities. 2) Macadam was the largest stock (111 million tons), while stone mastic asphalt, polyurethane plastics, and atactic polypropylene accounted for smaller components of the overall system. 3) The stock per unit area of pedestrian overcrossing was higher than that of the other stock units in the entire system, and its steel stocks reached 0.49 t/m^2, which was 10 times as high as that in interchanges. 4) The high stock areas were mainly distributed in ring-shaped and radial expressways, as well as in major interchanges. 5) Expressways and arterials were excessively emphasized, while minor roads were relatively ignored. However, the variation of cross-sectional thickness in branches and neighborhood roads will have a significant impact on the scale of material stocks in the entire road system.

1. Introduction

Urban development dominated by human activities is always accompanied by resource depletion and environmental pollution (Goudie, 2009; Rees, 1992). Cities play a central role in tackling climate change: They occupy only 2.4% of the Earth's land mass but consume 75% of the energy and emit 80% of the greenhouse gas in terms of human activity (Satterthwaite, 2008). With the urbanization process accelerating and population growing worldwide, the study of the input, store and output of materials and energy in urban systems has gained increasing attention. By characterizing the processes of urban metabolism, researchers aim to reveal the causations of environmental and resource-related issues and develop appropriate regulatory measures accordingly (Brunner, 2007; Gandy, 2004; Kennedy et al., 2011).

As the major component of municipal infrastructure, urban roads occupy approximately more than 25% of a built-up area. Road networks constitute the pivot for urban economic development, as their wide distribution and highly developing speed are far ahead of other artificial facilities (Wee, 2012). However, the acceleration in construction

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activities has directly led to an increase in material use and energy consumption, as well as a significant accumulation within the borders of cities. Eventually, these stocks will pass their use stage, and all or part of them will be discharged as waste into the environment or be recycled and reused (Han and Xiang, 2012). For analyzing resource appropriation and recycling, as well as the environmental impacts on urban ecosystems, it is crucial to quantify the material stock (MS) (Kennedy et al., 2007; Kovanda et al., 2007).

China is undergoing a process of rapid urbanization. In 2011, the built-up area on mainland China reached 43,603 km^2, with total road length and total road area jumping to 294,443 km and 5213 km^2, respectively (MOHURD, 2011a). During this period of high-speed economic growth and continuous environmental degradation, it is of great importance to quantify the infrastructure stocks in China's megacities, especially in terms of assessing stocks in urban road systems. However, due to the limitation of data availability, quantitative studies are rare.

To fill the current gaps in the research, this paper involved the development of an integrated model for calculating the MS of urban road systems. The model incorporated all levels of roads, intersection structures (curb curve and flared intersection) and ancillary facilities into an integrated framework. On the basis of a bottom-up method, the model provided a solution for data unavailability and unknown inner structure. The combination with GIS enabled the model to cope with the complex structures of road networks and avoid double counting. Then, the model was applied in Beijing by determining local parameters, with the subsequent conducting of a series of analyses. The application of this model can provide guidance for improving existing models of urban metabolism and optimizing urban infrastructure planning and resource management.

2. Literature review

2.1. A brief review of urban metabolism

In 1965, Wolman quantitatively simulated the input and output of the overall fluxes for a hypothetical American city (Wolman, 1965). Although the infrastructure materials and other durable goods were omitted, his work is considered the pioneering work in the area of urban metabolism studies.

Over the past 40 years, significant progress has been made in the following aspects: 1) Comprehensive case studies were conducted sequentially, in such cities as Brussels, Hong Kong, Sydney, Taipei, and Toronto, which represent different geographic regions and development levels (Duvigncaud and Denayer-DeSmct, 1977; Huang et al., 2001; Newman, 1999; Sahely et al., 2003). 2) Other less-comprehensive studies focused on specific domains, such as household consumption, construction systems, urban waste, and urban industry (D'Alisa et al., 2012; D. Hu et al., 2010; Liu et al., 2005; Tarr, 2002). 3) Meanwhile, some studies targeted certain elements or materials, such as nitrogen, phosphorus, heavy metals, and PVC (Forkes, 2007; Hedbrant, 2001; M.M. Hu et al., 2010; Kleijn et al., 2000; Li et al., 2012). 4) Methods: a trend from the Odum School's Emergy Analysis, MEFA (Material & Energy Flow Analysis) with LCA (Life Cycle Assessment) and Ecological Footprint Analysis, to Input-Occupancy-Output Analysis-based nonlinear and structured analysis combined with the state-of-the-art technologies of GIS and remote sensing.

2.2. Review for MS and its methods on an urban scale

Estimations of the in-use societal stock have been made for approximately 70 years, with over 70% of the publications occurring after 2000 (Gerst and Graedel, 2008). Within this rising trend, attention has gradually been paid to the accumulation of urban stocks from the perspective of urban metabolism in recent years, in which massive materials shift from the lithosphere into the anthroposphere and form buildings, infrastructure, and durables with a long life cycle (Baccini, 1996). As shown in Table 1, a number of works have examined different aspects of urban stock and there has been a gradual transition from the general MFA method to a mixed method integrated with GIS and multi-source dataset, providing a large boost to the development of the study of urban metabolism.

Despite the recent boom, studies on urban stock continue to be limited by data collection (Sahely et al., 2003). Since relatively complete industry data can be found only in a few developed countries, many previous studies have adopted a top-down method, in which the Net Addition to Stocks (NAS) that enters a stock system within a specified period is calculated by determining the difference between input and output fluxes (Kovanda et al., 2007). This inevitably led to the use of macroeconomic data, such as interregional input–output tables and statistical yearbooks, among other sources. The metabolic units at various levels were usually treated as black boxes or grey boxes, which can be measured in terms of their input and output without

Table 1
Chronological review of studies in material stock on urban or regional scale since 2000.

Authors, year	City or region of study	Analysis year	Objects of study	Model/method
(Hedbrant, 2001)	Stockholm (Sweden)	1900–2000	Heavy metal stock (Cd, Cr, Cu, Pb, Hg, Ni, Zn)	A spreadsheet model based on MFA
(Kleijn et al., 2000)	Sweden	1950–2100	PVC stock	Substance flow analysis
(Tanikawa et al., 2002)	Kitakyushu (Japan)	1970, 1995, 2020	Roadway and building	MFA with GIS
(Muller, 2006)	Netherlands	1900–2100	Dwelling stock	A stock dynamics model based on MFA
(Schiller, 2007)	Germany		Road and utility infrastructures	Material flow model
(Kovanda et al., 2007)	Czech Republic	2000–2002	Infrastructures, buildings, durables	Economy-wide material flow accounting and analysis
(Yamaguchi et al., 2007)	Osaka (Japan)	2007	Urban building, infrastructure	A bottom-up model
(Bergsdal et al., 2007)	Norway	1900–2100	Dwelling stock	Dynamic material flow analysis
(Lichtensteiger and Baccini, 2008)	Switzerland	1900–2000	Buildings stock	MFA combined with ark-house method
(Tanikawa et al., 2009)	Japan	1975–2004	Urban subsurface stock	Statistical methods integrated with GIS database
(Matsuno et al., 2009)	Japan		Copper, steel, aluminum in urban	By using DMSP/OLS nocturnal images
(Daigo et al., 2009)	Japan	2005	Stainless steel stock	Material Stock and flow analysis based on mass balances of Cr and Ni
(Tanikawa and Hashimoto, 2009)	Manchester (UK) and Wakayama (Japan)	1850–2000	Buildings, roadways and railways	A 4d-GIS model
(McMillan et al., 2010)	United States	1948–2006	Aluminum in-use stocks	Dynamic material flow analysis model based on top-down approach
(D. Hu et al., 2010)	Beijing (China)	1949–2008	Urban residential buildings	Material and energy flow analysis
(Diamond et al., 2010)	Toronto (Canada)	2010	PCB stock	PCB inventory
(Dall'O' et al., 2012)	Lombardy (Italy),	1919–2010	Residential building stock on an urban scale	A mixed method combined top-down with bottom-up
(Han and Xiang, 2012)	China	1978–2008	Residential buildings, roads, railways, and water pipelines	Statistical methods