Resource Consumption of New Urban Construction in China

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Summary

The volume of China’s recent additions to its urban-built environment is unprecedented. China now accounts for half of all new building area in the world. Increases in building stocks of all types have occurred during an extended period of accelerated growth of the national economy. This expansion promises to continue through 2030. As a result, the rapid conversion of land from low-density agricultural and light manufacturing to new urban zones of high density and material-intensive commercial and residential buildings has consumed enormous quantities of domestic and imported resources and has irreversibly altered the Chinese landscape. This article examines the consumption of material resources dedicated to Chinese building construction through a survey and analysis of the material intensity of three major building types. This provides a basis for outlining the emerging life-cycle issues of recent additions to the built environment and of continued construction. With this as the starting point, the field of industrial ecology can work toward formulating strategies for a circular economy that include a resource-efficient urban China.
Introduction

China’s economy has recently surpassed that of France, Britain, and Italy to become the fourth largest in the world behind the United States, Japan, and Germany. Fueled by double-digit yearly growth, the nation has crossed this threshold as the result of the phenomenal momentum of a liberalized modern economy (Bradsher 2006). Increased consumer spending, automobile and home ownership, small business creation, and many other indicators of market activity show an economy that is far from slowing. In fact, although the country’s leaders are intent on raising per capita gross domestic product (GDP) to US$3,000 and quadrupling the economy from 2005 to 2020, many experts suspect that even official indicators of economic activity published by the central authorities underestimate the true size and growth rate of the economy.

The majority of China’s existing industries and many newly founded business sectors have participated in this expansion. The construction industry in China is no exception. Construction expenditures have continually increased from US$267 billion in 2003 to a projected US$460 billion in 2008. Employment in construction has increased from 2% of total employment in 1990 to 5% in 1998. Annually, and for the foreseeable future, China builds roughly half of all new building volume in the world. From the late 1990s until 2004, China added between 1.5 billion and 2 billion square meters (m²) of space annually¹ (Lang 2004; National Bureau of Statistics 2005). New construction in large cities accounts for approximately 55% to 60% of this development activity. By 2020, it is estimated that 20 billion to 30 billion m² will be added to Chinese cities and suburban areas, according to Qiu Baoxing, the vice-minister of construction (Xinhua 2006a). Therefore, an annual addition to building stock in China of 1.5 billion to 2 billion m² is probable until 2020.

The additions of enormous infrastructure projects and thousands of new buildings have fundamentally altered the character and resource consumption of Chinese urban centers. Cities have expanded their footprints and swallowed huge swaths of agricultural land in an effort to satisfy the market’s demand for new commercial and residential space. Because it is the result of economic reforms and liberalized laws on property ownership, the intense development has not been a surprise to the government. Yet an early national urban policy aimed at controlling and directing urban expansion has been seriously compromised in its implementation and influence (Wei 1994). The 1989 City Planning Act was intended to enable cities to re-establish control over their development and growth. This act allowed cities to regain the primary role in regional development, partly by limiting urban sprawl into surrounding rural areas. However, the 1989 Act was soon rendered ineffective by two factors: the demand for residential and commercial space precipitated by the liberalized economy, and the creation of huge income disparities between successful land speculators and rural farmers.

What are the ramifications both domestically and globally of this intensive development of the Chinese urban environment? How are the short-term and long-term effects related and what can we foresee as important issues arising from this development? Finally, how does the intensity of this construction activity affect the resource burden and future consumption of the built environment?

The Urbanization of China

Between 1953 and 2003 the population of China doubled, while the urban population tripled. Six hundred and sixty cities are now home to more than half a billion of the total Chinese population of 1.3 billion. By 2020 the country’s population is expected to reach 1.45 billion. A majority of the population now lives in the cities of the Central and East regions of the country, areas that together account for two-thirds of the nation’s economic activity (figure 1). China’s intensive urbanization has produced 170 cities of one million or more residents each. Several cities in these regions have been expanding at unprecedented rates. For example, in 2005 Shanghai alone added more space in the form of residential and commercial towers than exists in all of New York City (Barboza 2005).

Accompanying these population increases has been a voracious land grab, by both local
governments and private developers, which has extended the area of many of the largest cities well into the agricultural countryside (Liu and Diamond 2005). Early in the 1990s, urban planning initiatives to control this expansion into the countryside included ideas such as the creation of relatively small satellite cities surrounding the largest urban cores and connected with relatively compact transportation corridors. These plans were quickly overrun, however, by the sheer volume of development pressure driven by economic reform and population migration, and many Chinese cities have expanded well beyond any previous projections of area limits, by annexing townships and suburban and rural counties (Wei 2005). In addition, many previously defined counties simply acquired enough urban population and gross domestic product (GDP) to be reclassified as cities, a process of city upgrading from county level known as xian gai shi (Ma 2002) (meaning county becoming a city).

These trends have been the result of a coupled set of policies freeing the economy from central and planned control, beginning with a series of actions establishing economic liberalization in 1978 and culminating with the official designation of all housing as “market” on July 1, 1998. Political decentralization has also provided local authorities with the power and resources to direct local development. In addition, the household registration system previously coupled with employment has been discontinued. This has allowed for the rapid creation and evolution of land and housing markets.

**Resource Consumption of Construction in China**

Broadly, the activities of the construction industry are organized into two sectors: infrastructure and buildings. Infrastructure construction includes transportation; power
generation and distribution networks (including dams for hydroelectric energy production); water collection, distribution, and treatment; and solid waste treatment and disposal. Much of this construction has been distributed roughly equally between the efforts to connect cities and to develop improved transportation networks within municipal boundaries. According to Li Shenglin, minister of communications, China intends to connect all administrative villages (mid-size towns) with highways by 2010 and to maintain the construction of rural highways as a high priority. In 2006 alone, China planned to build 180,000 km of rural highway² (Xinhua 2006b).

China’s dedication to infrastructure investments has been consistently strong over the past two and a half decades and accelerating over the last ten years. Infrastructure constitutes the major delivery networks of a city; highways and roads, water supply and distribution, power plants and the electrical grid, and waste collection and disposal. Between 1980 and 1999 the total national investment in fixed assets grew by a factor of 33! During the 1990s the average annual growth rate in fixed asset investment averaged 10.6% (Shirong 2001; National Bureau of Statistics 2000). Total 2004 investment in fixed assets amounted to 7 trillion RMB Yuan,³ an increase of 26.6% over 2003. Cities and local authorities have also invested heavily in infrastructure projects. For example, Beijing’s investments in infrastructure for the period 2006–2010 will constitute 60% of the city’s fixed asset investment for that period.

Generally, the volume and value of construction dedicated to infrastructure projects exceeds that of buildings. This is especially true in China, where infrastructure investment at the national, regional, and municipal levels is at a historical high. By 2010, 81 new power plants of 200 MW or greater capacity⁴ are planned, and massive highway, rail, subway, and airport projects have been funded as part of China’s Five-Year Plans focused on energy, transportation, telecommunications, water, and waste (Shirong 2001; National Bureau of Statistics 2000; Thomas and Wilson 1998; Wen and Wang 2000).

Alongside infrastructure investment, public and private funding has been directed to provide sufficient housing for new city residents. Due to enormous demand, construction of housing space constitutes approximately 80% of all new space added to China’s building stock. Therefore, because of the material intensity of housing and to a lesser extent commercial buildings, these building types dominate the resource consumption of the new building stock and the overall urbanization of the country. For example, a six-floor residential building will consume approximately five to eight times the volume of materials used in an industrial building of comparable floor area; a 50-story commercial office building will consume two to five times the volume of materials of a comparable industrial building (figure 2). This is due to the more demanding needs of users in commercial and residential buildings requiring greater volumes of materials for interior partitions, ceilings, floor and wall finish materials, water and electrical fixtures and distribution devices, lighting, heating and air conditioning, and other space-defining and service-providing elements. In contrast, most industrial buildings consist of relatively large and open spaces of relatively light material content.

The graph in figure 2 assigns a material content score of 100% to residential buildings, the building type of greatest material concentration. Therefore, to enclose the same floor area, commercial buildings require approximately 62% and industrial 13% of the bulk volume of the material required by residential buildings. These proportions are derived from a survey of more than 50 buildings of these three types from the United States, Europe, Canada, and Japan. The survey was conducted in the Building Technology Program at the Massachusetts Institute of Technology.

Commercial and residential buildings have been the primary agents for the rapid urbanization of China. Increases in the number of commercial establishments, especially small businesses, and the exponential growth of the housing market have driven forward strong demand for sustained development and urbanization. Decoupling employment and housing has spurred a great development surge in residential construction. China devotes approximately 65% of its construction expenditures to improving, replacing, and adding to the housing stock (Rousseau and Chen
Therefore, recent construction of the built environment in China not only has progressed at an increasing pace but has been focused on the building types of greatest material content: residential and commercial buildings.

This increase in commercial and residential buildings has begun to influence the long-term resource burden of Chinese cities. Currently China's per capita energy usage is well below most developed nations at 50% of the global average. Spurred by economic development, improvements in the standard of living, increases in the volume and diversity of consumption, and large-scale migration to urban areas, per capita energy consumption will approach that of developed nations within 10 to 15 years. This will be due, in part, to the fact that in 2015 half of all residential space then existing in China will have been built since 2000 (Zhu and Lin 2004). From the year 2000 through 2030, China and India together will likely account for half of the increase in residential energy use of non-OECD (Organisation for Economic Cooperation and Development) countries (IEO 2006).

**Differences between building types may be examined by deriving the material intensity of each.**

As stated above, the material intensity of industrial use per square meter of building area is far less than that of either residential or commercial use (figure 2). Despite the diversity of building types and a growing variety of building materials and products, much of the new building mass in China consists of a large proportion of a limited number of structural and nonstructural materials. Many developed countries have access to between 30,000 and 50,000 distinct building materials and products. China's recent market has only been able to offer approximately 2,000 to 4,500 materials and products for construction (Shirong 2001). Chief among these is reinforced concrete.

For commercial and residential multi-story buildings in China, concrete is the preferred structural and exterior wall material (figure 3) (Shirong 2001). Today China is the leading producer of concrete and accounts for one half of

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**Figure 2** Approximate material content (by volume) per unit of constructed area for three building types in China (2005).

**Material Content of Typical Chinese Construction**

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_Fernández, Resource Consumption of New Urban Construction in China_
Figure 3  Typical Chinese residential buildings (photos courtesy Prof. Leon Glicksman, Massachusetts Institute of Technology).
global demand. Concrete, along with brick, is also extensively used as the primary material for interior partitions. Studies show that global concrete production accounts for 3% to 8% of total anthropogenic carbon emissions (Chaturvedi and Ochsendorf 2004; World Resources Institute 2004; World Business Council for Sustainable Development 2002; Worrell et al. 2001; Mehta 1998). Along with the construction of roads, dams, and other concrete-intensive structures, the overwhelming use of concrete in buildings accounts for the fact that China currently far exceeds all countries in carbon emissions resulting from the manufacture of cement clinker and concrete (Low 2005; Van Oss and Padovoni 2003). In contrast, China is the leading producer of crude steel in the world but the material is not used widely in building construction within China.

Given the preponderance of the use of concrete in Chinese buildings, it is possible to attempt an overall accounting of a large portion of the resource consumption of construction in recent years. We will also be able to roughly ascertain the resource requirements for the residential, commercial, and industrial space that will be demanded in the coming decades.

Tables 1, 2, and 3 of the e-supplement (electronic supplement available on the JIE Web site) list primary materials used in the construction of the structure and exterior envelope of contemporary Chinese buildings. These systems consume the bulk of the material volume required of these buildings. Standard thicknesses for material components are shown, and area and volume calculations assume standard floor-to-floor heights and other typical dimensional attributes.

Material volumes were obtained through a survey of typical Chinese construction. Material volume measurements from a total of 16 construction documents of housing, commercial, and industrial buildings collected from previous studies, and current designs were made to determine the overall material content of the 100-m² area modules. Although Chinese design is now host to a dizzying array of forms, the construction methods to realize these buildings are of limited diversity. This limitation allows for an accurate survey of the material content of the three major building types examined here.

Results of the survey show material volume totals for each building type are 52.62 m³ for residential, 28.7 m³ for commercial, and 6.3 m³ for industrial. These figures closely approximate the general proportions for material content of the three building types illustrated in figure 2. Of course it is important to remember that this study can only approximate typical material content for each building type. The definition of material intensities used here is volume of construction material per unit of constructed area of interior space. This simple ratio quantifies the construction material requirement (in volume) of providing one unit of service (constructed floor space):

\[ MI = \frac{M_{volume}}{A_{constructed}} \]

where \( MI \) is material intensity, \( M_{volume} \) is volume of construction materials, and \( A_{constructed} \) is area of interior space.

The calculated values are shown in the last column of tables 1, 2, and 3 of the e-supplement. Again, the material intensities approximate the relation between the building types found in figure 2. That is, residential construction is clearly more material intensive than either industrial or commercial construction: 6 times and 1.3 times more, respectively (figure 4).

Global Resources and Chinese Urbanization

Urbanization in China today is claiming resources from well beyond its national borders and changing the profile of competition for resources globally. Of the US$454 billion global market in construction materials in 2004, the Asian Pacific region accounted for 58% of sales. Europe accounted for US$82.5 billion, second largest and an 18.2% share, and the United States accounted for US$34.8 billion and 7.7%. Concrete amounts to 27.3% of the global market. Total world production of concrete in 2005 reached 2.28 petagrams (= billion tonnes) of which China produced 46%, or 1.064 petagrams. East Asian production of concrete, including China, has increased 60% since 2000.

As shown above, residential buildings require more material than commercial buildings and a great deal more than industrial buildings per...
constructed area. Residential buildings also account for approximately 80% of new construction (as measured by interior area constructed). Therefore, assuming projections for future construction volumes, it is possible to calculate total material requirements for additions to building stock.

Using our definition of material intensity, for every unit area of residential space produced (m²), the overall mix of materials required (as listed in table 1 of the e-supplement) is equal to a volume of 0.36 m³. For commercial this is 0.28 m³, and industrial, 0.06 m³. For concrete alone, the figures are 0.32 m³ for residential, 0.27 m³ commercial, and 0.059 m³ industrial. If projections of an average of 2 billion m² of new construction yearly remain constant and residential construction accounts for 80% of that total, the yearly amount of concrete required for new housing construction will be approximately 512 million m³. Depending on the proportion of commercial construction, the requirement for concrete for this type of construction may be 27 million m³ (assuming 5% of total construction volume) or 65 million m³ (assuming 12% of total construction volume). Industrial construction will require much less—on the order of 6 million m³ (assuming 5% of total construction volume).

Therefore, an annual total of as much as 583 million m³ of concrete will be required. The weight of Portland cement concrete with aggregate is 2.4 tonnes/m³ (2,371 kg/m³). Therefore, a total annual requirement of 1.4 petagrams (1.4 billion tonnes) of concrete will be needed annually for the next two decades for new construction of buildings alone. As stated previously, world production of concrete in 2005 was 2.28 petagrams, of which China contributed 1.064 petagrams. Annually China will need to continue to import a net of at least 400 teragrams (= million tonnes) of concrete for the foreseeable future, almost 30% of its annual requirement. It is important to note that this satisfies demand only for building construction, not infrastructure.

This huge import requirement exposes China to risks associated with global shortages and varying transportation and fuel costs. These volumes will also require substantial imports of fuel and associated materials. The production of the fine granule clinker of Portland cement, the primary binding material in concrete, consumes approximately 3.2 to 6.3 GJ of energy per tonne. The total annual energy consumed in the making of the required volume of clinker necessary for Chinese building construction is a staggering 4.5 exajoules (4.5 × 10¹⁸ joules).
Also, studies have shown that site-cast concrete is generally the most energy-intensive structural system for building construction, compared with steel or wood. The critical factors in this comparison are the much greater transportation energies devoted to bringing workers and equipment to the construction site for this labor-intensive system. This research shows that 7% to 10% of embodied energy for building structural systems may be attributed to construction processes, whereas site-cast concrete, requiring many workers and heavy equipment, can contribute as much as 25% of the total embodied energy (Cole 1999). As more Chinese workers begin to acquire automobiles, the energy consumed in casting concrete buildings will increase as those workers travel to construction sites. Since 1993 China’s oil consumption has exceeded its production, placing greater pressure on energy costs for transportation. Therefore, continuing to construct buildings of concrete will be accomplished at a resource premium. Imports that serve this sector of the energy market will likely increase and compete with demand from other countries.

Aside from concrete, it is clear that the acquisition of a variety of construction materials to support China’s urban expansion will be a challenge. The industries that produce glass, steel (particularly for steel reinforcing of concrete), aluminum, synthetic and natural polymers, and other materials are already experiencing shortages and price increases due to China’s growth.

## Emerging Life-Cycle Concerns for Urban China

Urban planners, politicians, and scholars of China refer to the recent period of economic and political reform as the transitional period. This corresponds to the changing nature of Chinese urban zones and their global resource demands (Yeh and Wu 1999; Zhou and Ma 2000; Ma 2002). Currently, much of the resource requirement pressure is focused on materials for construction. This is changing every day as additions to building stock are completed and demands for operation energy increase.

It has been shown that the metabolism of rapidly expanding cities in developing countries generally progresses from a material-intensive period of infrastructure and building construction to a phase of increasing energy demands (Bindé 1998; Tyler 1996). Increasing urban populations contribute to these energy demands as consumption for air conditioning, household appliances, and transportation climbs. A general diagram of this progression is shown in figure 5.
Per capita energy consumption in China has lagged far behind that of many developed nations: in 1999, 700 kilograms (kg) of oil in China versus 6,902 kg in the United States, 7,825 kg in Singapore, 3,277 kg in Japan, and 952 kg in Turkey (World Bank 1999; World Resources Institute 2001). Urbanization is, however, beginning to create pockets of resource consumption in China at the level of developed countries. The Yangtze Delta area (around Shanghai) in particular is host to a number of cities with residents earning twice the average national GDP per capita and consuming more than twice the electricity of the national per capita average (Gao et al. 2004; see figure 6). It can be seen that this upward trend accelerated during the mid-1990s.

Clearly the intensity of economic development, growing per capita income, and liberalization of the economy will likely drive this consumption steadily upward for the foreseeable future.

In fact, signs have occurred that economic development is already outpacing the production of adequate amounts of energy in China. Several of China’s fastest growing cities, such as Shenzhen and Chengdu, regularly record massive blackouts during the summer air conditioning peak. In 2004, more than 60% of China’s provinces, municipalities, and autonomous regions experienced sustained shortages of power (Aldhous 2005). In addition, China’s continued reliance on coal threatens to worsen the already noxious air quality of many of the fastest-growing cities. Three-quarters of the Chinese urban population now lives with air quality that does not meet even local Chinese standards. Seven of ten of the worst polluted cities in the world are located in China (EIA 2006).

Buildings are a major consumer of energy in China. As urbanization continues, the proportion of total energy dedicated to the building sector will grow from approximately 28% in 1999 to a range of 35% to 40% between 2030 and 2050, a range more typical of fully developed countries (Zhu and Lin 2004). As stated above, the substantial addition of building volume promises a significant increase in the intensity of fuel-related resource consumption in China. Although it can be argued that dense cities of developed nations are more energy efficient than low-density regions, this may not be true of China. The expansion of Chinese cities is occurring simultaneously with a tremendous increase in the standard of living and subsequent resource burden. In addition, the pace of demand for new space and the inability of local authorities to inspect new construction are resulting in the widespread construction of low quality buildings. Many new Chinese buildings do not meet energy standards established by the Ministry of Construction.

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**Figure 6**  Per capita annual electricity consumption for a selection of Yangtze Delta cities along with the national average. One kilowatt-hour (kWh) ≈ 3.6 × 10^6 joules (J, SI) ≈ 3.412 × 10^3 British Thermal Units (BTU). Source: Gao et al. 2004. Reprinted with permission from Elsevier.
Today, Chinese residential building energy consumption (per square meter) is twice that of residential buildings in developed nations of similar climates (Lang 2004). Throughout the late 1990s and early in this decade, residential building energy use per unit of building area increased at a rate of 16% annually (Rousseau and Chen 2001).

It is also well established that the energy-related resource consumption of a building during its long service life accounts for the bulk of its total resource consumption. This use-phase consumption consists almost entirely of fuel resources converted to electricity for lighting, heating, and air conditioning of building interiors.

These issues presage a period of challenging energy demand. Many new buildings are designed to serve for at least 50 to 75 years with normal maintenance and repair but are typically in service for much longer—often two to three times longer. Underperforming buildings will continue to waste energy for decades to come. Commercial and residential buildings normally consume 80% of their life-cycle energy during this long use phase. The remaining 20% is partly accounted for in the embodied energy of materials of construction (approximately 12% to 18%) and energy in demolition (approximately 2% to 8%) or other end-of-life processes.

Figure 7 delineates this resource consumption by depicting the life cycle of a building and its attendant consumption. Resource content can be measured in several ways, but one can conceptualize the term as the energy equivalent of consumption during that stage. Therefore, during the pre-use phase $0-A_t$ (corresponding to construction), the total resource consumption amounts to $A_{rc}$, a mere 12% of total resource content of the building. The long-use phase, often more than several generations for many buildings, consumes approximately 80% of the total resources used ($B_t$ and $B_{tc}$). It has been shown that the total embodied energy of construction materials used in a typical building (residential or commercial) is less than the operating energy in only four to
The enormous increases in the Chinese urban building stock have only just begun to engender their lifetime resource consumption. Along with many other aspects of the consumption of resources, the built environment will contribute to the increase in the per capita consumption of the Chinese population over the next several decades. A rise to developed-world consumption levels will mean that global resource use will double, at the very least. If energy consumption by the built environment also reaches proportions of consumption found in much of the developed world, Chinese urban centers will consume close to 40% of total national energy production. Easeing this energy consumption downward would have a significant global impact.

As shown above, the nature of resource consumption due to the expansion of Chinese cities will steadily shift from a nonfuel material-intensive set of construction activities to a fuel- and energy-related burden. Although China has aggressively and successfully reduced its energy input per unit of industrial production, it has not been nearly as effective in reducing the energy intensity of residential and commercial space. Inconsistent application of insulation materials, poor workmanship in sealants and other substandard joining in the exterior wall, poor-quality structural concrete and insufficient steel reinforcing, poorly maintained air-conditioning and heating units, and substandard windows and doors are only a sampling of the problems that typically arise from low-quality construction due to rapid development of large properties and the accelerated schedules required by the Chinese real estate market. All of these problems, and many more, are endemic to the housing construction market and threaten to characterize a wasteful future. Recently, some indications are that construction quality is improving. The Ministry of Construction has been actively engaged in establishing progressive guidelines and targets for energy-efficient buildings, but enforcement has been notoriously lax or completely absent.

In addition, many of the most rapidly growing cities in China do not either possess or adhere to urban design master plans. It is very common for redevelopment pressures to initiate waves of massive demolition of structures only a few years old. Although some of this demolition is catalyzed by a reasonable desire to upgrade poorly constructed buildings, much of it is simply due to land value increases, development speculation, and large annexations of surrounding areas. Chéxian sheshi (abolishing the county and establishing a city) and zhéngxian gaishi (entire county becoming a city) must be planned for in ways that make sense with available resources.

In any case, three important ramifications of the continuing urbanization of China should be noted.

1. There will be a continuing demand for the importation of building materials. China does not possess the resources necessary to continue urbanization at the pace of recent years. Significant quantities of materials for construction will be a primary way in which China continues to develop diversity in its building materials market.

2. The geographical expansion of large cities and their transformation into polycentric urban zones will dramatically increase the demand for transportation between residential areas and places of employment. The possibility for these cities to begin developing low-density suburbs poses even greater transportation problems for the future by requiring workers to increase their commuting distances. The burden on fuel resources for transportation will be a major component of future increases in energy needs.

3. Massive infrastructure and building construction in the next 30 years will continue to add to the energy demands of urban centers. The energy that these new megacities will require is a global energy priority. China has been actively searching for energy resources all over the world because it correctly assesses that the results of rapid urbanization necessitate a diversified and reliable energy supply. This energy demand will increase steadily and will most likely lead to the long-term use of coal as the primary fuel for building energy.12
The Circular Economy and the Design of Buildings and Cities

It is the province of industrial ecology to consider these three ramifications and propose ways in which symbiotic industrial relationships can promote societal resource efficiency and reductions in national and global environmental degradation. These priorities are not new to the State Council and the two central government agencies responsible for developing strategies for sustainable development: the State Environmental Protection Administration (SEPA) and the National Development and Reform Commission (NDRC). Guiding the development of individual strategies is the notion of a circular economy (CE): generally considered an arrangement of firms and industrial activities that both supports economic growth and facilitates the closing of material loops and the overall promotion of resource efficiency. Lately, the NDRC has been given primary authority to promote the establishment of a CE at three levels: the individual firm (micro), collections of firms as eco-industrial networks (meso), and at the city, regional, and provincial scale (macro). The CE in China is now regarded as integral to economic development (Yuan et al. 2006).

This article can only briefly address the construction sector of a future CE in China. For example, studies should establish the opportunities for the built environment for utilizing industrial by-products of an expanding energy sector. Correlating increasing concrete demand with the increasing availability of fly ash and other combustion by-products from coal is only the beginning. More work will be required to fully formulate the nature of a construction sector supportive of a successful CE. We can, however, propose here schematic roles for two distinct disciplines in supporting development of the Chinese CE: building design and technologies; and urban planning.

Building Design and Technologies and Urban Planning

Building design and technologies should be focused on maximum reduction, reuse, and recycling of construction materials and practical strategies for energy cascading and symbiotic resource exchanges among firms, industrial sectors, and cities and regions. These efforts should begin with improvements in the quality and sophistication of the technologies, materials, and design used to satisfy building space needs. Broad and simple improvements in the energy efficiency of buildings will contribute enormously to the operational energies of the new building stock.

Improvements in building energy efficiencies will come as a result of improved construction practices in the field and aggressive and sustained governmental regulation and enforcement. In many parts of China, personnel responsible for building inspections are overworked and cannot realistically enforce existing construction and energy regulations. Enforcement of policy and standards is absolutely essential to any progress.

It has been shown in many types of buildings that short-term resource consumption of construction materials and long-term consumption of fuel resources are linked by the quality of construction and the performance of specific building systems and devices (Keoleian et al. 2001). Although guidelines for substantially improving the life-cycle resource consumption of new buildings are well established, implementing such practices in the face of extraordinary economic pressures is challenging (Fernández 2006a; Kibert 2005). In addition, methods of appropriate material selection for energy-efficient buildings and environmental assessments specific to the metabolism of contemporary buildings should be investigated (Fernández 2006b).

Individual directives that will promote a CE of the built environment while developing the industry of construction include the following:

- Product design: Improve the performance of building systems, especially the exterior envelope and heating and cooling systems of buildings for the purpose of lowering the life-cycle resource burden of individual building types. Support domestic firms that offer high-quality building products and contribute to an emerging CE for building products should be a high priority. Various tools of life-cycle assessment need to be integrated into the design and engineering of buildings.
Industry design: Identify material and energy exchanges that can be supported by the government and industry as a mechanism toward “redesigning” the construction industry of China. Co-location of various components of diverse industries and subsidies that provide incentives for developing robust resource exchanges should be integrated into any economic policy that addresses the construction of the built environment. Physical accounting for all flows within and between firms as part of the entire industry of construction should be integrated into industrial planning.

City design: Analyze the metabolism of Chinese cities with particular emphasis toward characterizing the resource consumption of a variety of urban and suburban communities of different scales and climatic contexts to reveal opportunities for resource efficiencies in the design, planning, and operation of the built environment. Promote the intersection of design, technology, industrial ecology, and planning as a way of formulating a multiscale, multilevel understanding of the metabolism of the Chinese city. Material flow analysis (MFA) should be integrated into the suite of tools used by government and planning authorities.

Deng Xiaoping once remarked that Chinese economic reform, and by extension, urban development, can be thought of as crossing a river by “groping for stones” (Wei 2005). This incremental strategy admittedly allows for a continual reassessment of needs while posing significant risks by which even the best-laid plans are rendered quickly irrelevant and outdated. Avoiding unnecessary construction due to changes in infrastructure placement and engineering and limiting unanticipated demolition should become priorities for municipal authorities (Wei 2005). Easing into a process that is better directed by master planning enforced by city officials will ensure a better use of resources (Chen 2002).

Much further research regarding the role of rigorous urban planning for the environment and resource consumption is required to establish the potential for lasting effects on the landscape of China. In addition, further study is critically needed to establish the balance between dense urban centers, boundaries of urban expansion, acceptable levels of suburban development, and the transportation, power, water, and waste systems required to sustain a responsible rate of growth.

Conclusions

The enormous industrial metabolism of China is creating the largest and most rapidly urbanizing nation in the history of the world. The unprecedented additions to new urban building volume dwarf construction in any other country and will strongly influence the metabolism of Chinese cities, the nation as a whole, and the distribution of global resources for many decades to come. Today Shanghai boasts more than 4,000 skyscrapers (18 floors or more) of which 1,000 exceed 100 m in height, far more than New York City. Continued migration to the cities promises to displace more than 75 million farmers during the next five years and possibly 170 million in the next ten (Rousseau and Chen 2001). In addition, China’s population will increase by about 200 million in the next 25 years. If current trends continue (and refrain from accelerating further) 25% to 40% of that additional population will seek housing in urban areas. Together, this could result in between 125 and 175 million additional urban dwellers seeking housing. Much depends on what proportion of China’s new population seeks to migrate to urban centers.

To satisfy the immediately pressing need to house growing urban populations, Chinese cities are forced to construct material-intensive space by using energy-intensive concrete. Residential buildings will continue to dominate the resource consumption devoted to building construction. Short-term priorities to manage the resource consumption of materials used in construction and long-term strategies for steadily increasing the energy efficiency of the most energy-intensive buildings will reap substantial savings in resource consumption, with global implications. In addition, changes in the behavior of city residents may not necessarily lead to resource consumption at the levels of urban dwellers in developed economies of the West. There may be ways in which replacing physical implements with
services will receive greater acceptance in Chinese urban centers than in the cities of Europe and the United States. This is a segment of research that deserves greater attention.

Finally, building design and technologies integrated with urban planning are needed not only to assist with overall reduction, reuse, and recycling priorities but also in the redesign of the entire industrial network enlisted to produce the built environment. This requires that the tools and theories of industrial ecology, and the researchers themselves, be engaged at the three levels of developing a working and robust CE. It is critical that these efforts be undertaken within a context in which material and energy flows are tracked, recorded, and used to develop future targets that can verify or refute claims of progress. Although certainly ambitious, China’s adoption of the notion of a CE should encourage researchers to contribute in practical ways to the redesign of specific sectors of that society’s industrial metabolism.

Notes
1. One square meter (m², SI) \(\approx 10.76\) square feet (ft²).
2. One kilometer (km, SI) \(\approx 0.621\) miles (mi).
3. One RMB Yuan (¥) \(\approx €0.099\) Euro and $0.128 USD (January 2007).
4. One megawatt (MW) = \(10^6\) watts (W, SI) = 1 megajoule/second (MJ/s) \(\approx 56.91 \times 10^3\) British Thermal Units (BTU)/minute.
5. Tables 1, 2, and 3 are based on the following assumptions: (1) Materials selected are high-volume materials that constitute the structure, substructure, foundation, exterior wall, and roof assemblies. These assemblies contribute 75% to 90% of the material volume of buildings. Metals (aside from steel reinforcing of concrete) are not included because of variations due to programmatic attributes of the building. Also, the intensity of metal use in buildings is highly dependent on the arrangement of spaces and density of use, as with number of bedrooms and bathrooms per residential unit, for example. (2) Materials have also been selected to allow for comparisons across building types. Therefore, all buildings use concrete as the primary structural material. This is also the case for the industrial building, even though this type may also be built of steel. (3) Steel reinforcement of structural concrete has been averaged at a volume ratio of 5% of the total volume of the composite. This is the only application of metal accounted for here. Further studies are required to establish comprehensive material intensities for metals in residential, commercial, and industrial construction.
6. One cubic meter (m³, SI) \(\approx 1.31\) cubic yards (yd³).
7. This is not meant to indicate any kind of eco-efficiency. The basic differences between the volume of construction materials required to produce one unit area of residential space compared with commercial and industrial space is a factor of design issues and user needs such as the arrangements of interior volumes, the necessary additional interior partitions, a higher level of finish, and many other factors that cannot be placed within any kind of ratio that relates economic value to environmental impact.
8. One tonne (t) = \(10^3\) kilograms (kg, SI) \(\approx 1.102\) short tons.
9. One kilogram (kg, SI) \(\approx 2.204\) pounds (lb).
10. One gigajoule (GJ) = \(10^9\) joules (J, SI) \(\approx 9.48 \times 10^5\) British Thermal Units (BTU).
11. One exajoule (EJ) = \(10^{18}\) joules (J, SI) \(\approx 9.48 \times 10^{14}\) British Thermal Units (BTU).
12. Today China satisfies approximately half of its energy needs from a rich domestic coal supply. Between the years 1949 and 1979, coal production increased by a factor of twenty through the opening of 1,498 new coal mines. Recently, the percentage of energy provided by coal has fallen from a high of nearly 75% in 1996, primarily due to the need to introduce additional fuels to meet rising electricity demand and the increase in transportation fuels. Yet this decline may be over, as all forms of energy are exploited to their fullest to meet growing urban energy needs.

References


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