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Concrete transformation of buildings in China and implications for the steel cycle

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ABSTRACT

Urbanization and real estate development are two mighty impetuses for the growth of China. An enhanced dynamic modeling has been devised to explore stocks and flows of buildings in the country and to quantify the related steel cycle. The uncertainties of the variables and results are investigated by the means of Monte Carlo method and sampling analysis. The building stocks are expected to increase to some 85–130 billion m^2 in the mid-century, about 40–100% up from the current level. Throughout China but in urban areas in particular, concrete structures are replacing the buildings made of wood, clay brick, and primitive materials. By 2050 every two out of three buildings in China will be reinforced concrete- or steel-framed, leading to substantial demand for ferrous metals.

Scenarios analysis shows that a slowing down in the building stock expansion will likely occur in China in no more than ten years. This may open up a transition with profound industrial and resource implications. Increasing businesses for the construction industry may emerge from maintenance, retrofitting, and end-of-life management of existing buildings. The steel industry shall reform its capacity to conform to the growingly available secondary resources and the declining requirement for construction steel. Efficient and appropriate recycling of steel content from waste concrete will play an important role in material conservation. A collaboration of improvements in process material efficiency with lifetime extension and application of high-strength steel may save nearly 40% of primary iron ores for building use in the coming four decades.

1. Introduction

The twentieth century witnessed unparalleled development of an industrial society characterized by massive production and consumption of material resources and massive generation and disposal of wastes to meet human needs for nutrition, sanitation, habitation, transportation, communication, and recreation. Among them, probably no other demand used more materials by weight than housing and sheltering (Wernick and Ausubel, 1995; Krausmann et al., 2008). Construction, renovation, and demolition of buildings and the built environment generate hefty waste flows. Resource and environmental impacts of buildings are not only extensive but maintain long-term inertia, due to their long service lifetime. They also draw a sharp distinction between the developed and the developing countries: The former has had well-established building stocks, which require more renovation and retrofitting than new construction. But the developing countries, commonly accompanied with insufficient property and a low level of urbanization, have to complement and decorate their urban landscape with new buildings and infrastructure to accommodate a substantial rural population migrating to cities for better quality of life. New constructions usually mobilize far more construction materials than renovation and maintenance (Yang and Kohler, 2008; Yang, 2010), exerting pressures onto the fragile environment in the developing world.

China presents a vivid case for study of building development in a rapidly developing country. The percentage of registered urban residents in total population rose to 52.6% in 2012. It equaled to an annual increase of demographic urbanization by 1.2% since 1990, or each year 19 million people were moving from the countryside to urbanized areas (the National Bureau of Statistics of China (NBSC), 1991, 2013). Urbanization combined with desire for bigger residential space stimulated a vast campaign of construction. Total building floor space in urban regions surged to 34 billion

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(10^9) m^2 as of 2012, up from 5.9 billion m^2 in 1990. The floor areas of rural buildings also increased from 18 to 28 billion m^2, mainly driven by improved standard of living (NBSC, 1991, 2013; Yang, 2010). Construction minerals in total took over two-thirds of direct material input into the Chinese economy (Wang et al., 2012). China has become the world's largest producer of cement since 1985 (U.S. Bureau of Mines, 1988, 1993) and the largest producer of steel as from 1996 (International Iron and steel Institute, 2001). In 2012 it produced about 58% of cement and 46% of crude steel in the globe (U.S. Geological Survey, 2013; World Steel Association, 2013). More than 30% of these steel and cement outputs might be used in buildings (Li and Ke, 2012; Zhang and Shangguan, 2012). Resource and environmental pressures caused by buildings will be amplified with the continuing expansion of building stocks.

A fair amount of studies have been dedicated to investigate the resource and environmental impacts of buildings in China. The research extended from city level (e.g., Warren-Rhodes and Koenig, 2001; Huang and Hsu, 2003; Hu et al., 2010a,c) to the whole country, exploring a quantity of issues including construction materials (e.g., Fernández, 2007; Hu et al., 2010b; Shi et al., 2012; Huang et al., 2013), construction and demolition waste (e.g., Shi and Xu, 2006; Lu and Yuan, 2011; Li et al., 2013), direct and indirect energy consumption and GHG emissions (e.g., Glicksman et al., 2001; Chen et al., 2008; Li and Yao, 2009; You et al., 2011; Chang et al., 2013; Evans et al., 2014), and other categories of environmental impacts (e.g., Chang et al., 2013; He et al., 2013).

Dynamic stock and flow modeling has proven to be a useful research method employed in many of the studies. Müller (2006) was one of the forerunners using this method for analysis of buildings and their environmental consequences. Building stocks (usually measured by building floor areas) within a certain region and time period are first computed by multiplying the region's population with the parameter of building stocks per capita. After knowing the stocks over time series and the lifetime of buildings, newly completed and obsolete building space per period (i.e., building inflows and outflows) can be determined by stock balance and lifetime distribution equations. The dynamics of stocks constitute a meaningful and solid basis for quantitative analysis. First, they can be applied to probe many resource and environmental issues. The building stocks can be converted to the stock and flow values of construction materials or the consumption of energy, by multiplying with parameters of material or energy intensities (Fig. 1). After the material and energy inventory is established, a variety of environmental impacts can be assessed. Second, it is the building stocks to offer direct services to people and define their lifestyles. Building space per capita, an indicator for the quality of life, can be explained by exogenous variables such as income, housing price, and consumer behavior. The environmental analysis is therefore coherently linked its socio-economic context. Moreover, the pattern of stock change is less affected by short-term market or environmental fluctuations – it is better suited for perennial analyses and forecasts.

We carefully reviewed three typical studies analyzing the dynamic stocks and flows of buildings in China, as presented in Table 1. Yang and Kohler (2008) and Yang (2010) simulated the evolution of building stocks until 2050. The results were used in a comprehensive life cycle environmental impact assessment covering both construction and building operation phases. Hu et al. (2010b) concentrated their research on residential buildings and steel in a long period of 1900–2100. They interpreted the implications of building stocks for the iron and steel industry. Huang et al. (2013) estimated the demand for major building materials from 1950 to 2050. Prolonging the building lifetime and strengthening the recycling of materials were identified to be two key measures to save raw material demand.

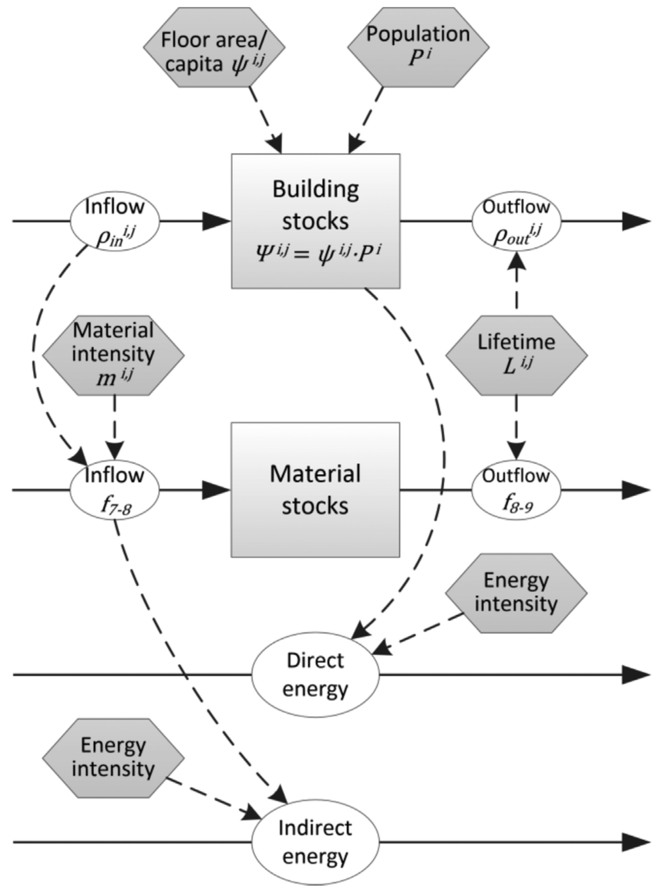

Fig. 1. Schematic diagram of dynamic stock and flow modeling of buildings. The rectangle represents stocks, the oval represents flows, the hexagon illustrates other determinants or drivers, the solid arrow depicts physical stock and flow relations, and the dashed arrow depicts the computation relations between the variables. The symbols (e.g., $\psi^{i,j}$) are interpreted in Table 2.

Comments onto these three studies include

(i) As a foundation for resource and environmental assessment, the determinants of the building stock dynamics need to be fully scrutinized. Huang's research did not propose alternative scenarios for population, urbanization, or per capita building stocks. Yang seemed to be over conservative when investigating future change of per capita floor space. For example, the areas of urban residential buildings would be increasing to a narrow extent of 38–40 m^2 per capita (m^2/cap) only in 2050 (Yang, 2010).
(ii) More thorough examination is needed for the material efficiencies of construction. Out of the three studies, only the research of Huang et al. (2013) differentiated the material use in brick-wood, brick-concrete (BC), and reinforced concrete (RC) structures. However, it might underrate the share of RC buildings in the urban stocks and lead to an underestimation of building steel use than reality.
(iii) The resource and environmental impacts were mainly assessed based upon current construction technologies and practices, which could not incorporate advancement of emerging technologies and prospective changes in process efficiencies and industrial structures. The issue can be partially solved by extending the material and resource analysis from the use stage to the total material cycle.

Accordingly, this present work aims to enhance the dynamic stock and flow analysis of buildings in China. Variables and