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Estimating the in-use cement stock in China: 1920–2013

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ABSTRACT

Cement provides a foundational function for buildings and infrastructures in the modern society. Huge amounts of cement have been consumed during the rapid urbanization process in China. Understanding the trajectory of the in-use cement stock could gain insight into the cement inflow, waste flow and associated environmental impacts. However, an economy-wide estimation for Chinese in-use cement stock is still lacking. Using the dynamic MFA, this paper seeks to provide a long-period (1920–2013) estimate for Chinese in-use cement stock in three branches (i.e., buildings, infrastructure facilities and agriculture facilities). To evaluate uncertainties inherent in the in-use cement stock, the Monte Carlo method is adopted here to calculate the confidence intervals of the results. The simulation results demonstrate that, at the end of 2013, Chinese in-use cement stock has reached 21.5 billion metric tons whilst in-use cement stocks of the building, infrastructure and agriculture sector are 17.3, 3.4 and 0.8 billion metric tons, respectively. During the recent decade, the per capita in-use cement has been experiencing a sharp increase from 2.1t/capita in 1992–15.8t/capita in 2013. The exponential growth of Chinese in-use cement stock underlines the need for prolonging the lifetime and reducing cement intensity of buildings and infrastructures to realize dematerialization in China. The estimation on the historical evolution of the in-use cement stock could lay a solid foundation for predicting the future cement demand and related environmental impacts. In addition, robustness of the estimation method has been validated by the uncertainty and sensitivity analysis.

1. Introduction

Cement is one of the three elementary materials (i.e., cement, steel and aluminum) consumed in building and infrastructure construction (Müller et al., 2013; Shen et al., 2014). Accompanying by the rapid urbanization process in China, unprecedented amounts of cement has been poured into the construction sector to satisfy the ever-growing demand in dwellings and accessorial infrastructure facilities (Cao et al., 2016). China's cement output has accounted for more than 60% of the world cement output in 2012 whilst the associated resource extraction and pollution emissions in the cement production have been recognized as an important issue for China's resource management and pollution control (Wang et al., 2016). Although the growth of China's cement production has slowed down in 2015 (NBSC, 2016), the ongoing urbanization and industrialization would still require a massive amount of cement. Therefore, to understand the future trend of China's cement consumption and to capture the related environmental impacts (Van der Voet et al., 2002; Van Ruijven et al., 2016), an in-depth investigation on the historical evolution of Chinese in-use cement stock is one of the underlying prerequisite (Pauliuk and Müller, 2014).

The dynamic material flow analysis (MFA) could depict a detailed picture for the temporal dynamics of the in-use cement stock, inflow and outflow (Kapur et al., 2008), instead of the static MFA that only provides a one-year snapshot of the material flows in the cement's life cycle (Wang et al., 2015a,b; Woodward and Duffy, 2011). The dynamic MFA has emerged as a powerful approach to portray the dynamics of various durable materials with a long life span (Müller et al., 2014), such as metals, organic chemicals, construction materials (see Table 1). According to the literatures listed in Table 1, efforts to estimate the in-use cement stock in China are scattered in several researches about the buildings or infrastructures (e.g., Han and Xiang, 2013; Hou et al., 2014; Huang et al.,

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Table 1
Researches using Dynamic MFA to estimate in-use material stock.

Material types	Methods	Time periods	Research countries/regions	References
PVC	Top-down	1950–2150	Sweden	Kleijn et al., 2000
Copper in water heating installations	Top-down	1965–2100	The Netherlands	Van der Voet et al., 2002;
CFCs in building foam	Top-down	1960–2080	Global	Van der Voet et al., 2002;
Lead in cathode ray tubes	Top-down	1988–2040	The EU	Elshkaki et al., 2005
Copper	Top-down	1900–2000	North America	Spatari et al., 2005
Concrete	Bottom-up	1900–2100	The Netherlands	Müller, 2006
Steel	Top-down	1980–2000	Japan	Daigo et al., 2007
Iron and steel	Top-down	1975–2000	The UK	Davis et al., 2007
Cement	Top-down	1900–2005	The United States	Kapur et al., 2008
Aluminum in passenger vehicles	Top-down	1975–2035	The United States	Cheah et al., 2009
Copper and copper-based alloys	Top-down	1950–2005	Japan	Daigo et al., 2009
Copper	Bottom-up	1990–2100	Global	Gerst, 2009
Construction minerals	Bottom-up	1970–2000	Japan	Hashimoto et al., 2009
Steel	Top-down & bottom up	1970–2005	Japan	Hirato et al., 2009
Lead	Top-down	1900–2000	Global	Mao and Graedel, 2009
Steel	Top-down	1980–2050	Global	Hatayama et al., 2010
Iron and steel in residential buildings	Bottom-up	1900–2100	China	Hu et al., 2010
Aluminum	Top-down	1900–2007	The United States	McMillan et al., 2010
Copper in buildings, infrastructure and mobiles	Bottom-up	1850–2050	Switzerland	Bader et al., 2011
Rare earth elements	Top-down	1950–2007	Global	Du and Graedel, 2011a
Rare earth elements in NdFeB permanent magnets	Top-down	1983–2007	Global	Du and Graedel, 2011b
Aluminum	Top-down	1900–2006	The United States	Liu et al., 2011
Iron	Top-down	1900–2005	Global	Müller et al., 2011
Steel	Top-down	1993–2020	Korea	Park et al., 2011
Aluminum	Top-down	1990–2009	The United States	Chen and Graedel, 2012
Aluminum	Top-down	1950–2009	China	Chen and Shi, 2012
Steel	Top-down	1940–2100	China	Pauliuk et al., 2012
Building materials in buildings and transport infrastructure	Bottom-up	1950–2050	China	Shi et al., 2012
Aluminum	Top-down	1947–2009	Italy	Ciacci et al., 2013
Metals in electricity generation technologies	Bottom-up	2010–2050	Global	Elshkaki and Graedel, 2013
Copper	Top-down	1960–2010	Global	Glöser et al., 2013
Construction materials	Bottom-up	1978–2008	China	Han and Xiang, 2013
Construction materials in buildings	Bottom-up	1950–2050	China	Huang et al., 2013
Aluminum	Top-down	1900–2100	Global	Liu and Müller, 2013
Cement, steel and aluminum	Top-down	1950–2010	Global	Müller et al., 2013
Steel	Top-down	1950–2100	Global	Pauliuk et al., 2013a
Steel	Top-down	1700–2008	Global	Pauliuk et al., 2013b
Zinc	Top-down	1900–2020	China	Yan et al., 2013
Steel	Bottom-up	2010–2050	China	Yin and Chen, 2013
Timber, iron, Other metals and nonmetallic minerals	Top-down	1930–2050	Japan and the United States	Fishman et al., 2014
Copper	Top-down	1975–2010	China	Zhang et al., 2014
PBDEs	Top-down	1970–2020	The United States and Canada	Abbasi et al., 2015
Aluminum	Top-down & bottom up	1964–2012	Austria	Buchner et al., 2015
Construction materials in wastewater treatment infrastructure	Bottom-up	1980–2050	China	Hou et al., 2014
Construction materials	Bottom-up	1945–2010	Japan	Tanikawa et al., 2015
Steel in buildings	Bottom-up	1950–2050	China	Wang et al., 2015b
Copper, aluminum, lead, iron	Top-down	2010–2050	China	Wen et al., 2015
Copper	Top-down & bottom up	1952–2012	China	Zhang et al., 2015
PVC	Top-down	1960–2012	The EU	Ciacci et al., 2016
Construction materials	Bottom-up	1978–2013	Beijing, Tianjing and Shanghai	Huang et al., 2016
Construction materials in sewer pipelines	Bottom-up	1984–2012	Japan	Lwin et al., 2016

2013; Huang et al., 2016 and Shi et al., 2012). It is noticed that most of those studies have employed the bottom-up method since the research scopes of those studies focus on various specific subsystems of the economic system. Müller and his colleagues have presented a global picture of the in-use cement stock from the top-down perspective (Müller et al., 2013). However, their study have not provided a detailed estimation of the in-use cement stock by segments in China and the average lifetime of cement adopted in their study is 65 years which is not in line with the reality in China.

Although the bottom-up method could provide more detailed information for the sector composition and spatial distribution of the in-use stock, it focuses on a limited number of sectors and might provide incomplete information about the in-use stock of the whole economic system (Wang et al., 2015a). A top-down method could provide a comprehensive economy-wide estimation of the in-use cement stock in China, which avoids incompleteness in results derived from the bottom-up method. To this aim, the present study attempts to assess the trajectory of the in-use cement stock and related flow characteristics in China from 1920 to 2013 with the dynamic MFA from the top-down perspective. The split ratio data for various branches are derived from the input-output tables and different branches are assigned with diverse lifetime distribution lifetime functions. Moreover, the uncertainties inherent in the dynamic MFA are evaluated by Monte Carlo simulations, and the effect of variations in parameters of the lifetime distribution function is investigated by the sensitivity analysis. Further, the per capita in-use cement stock in China is compared with a previous study about the in-use cement stock of the United States.

2. Methods and materials

2.1. Description of the dynamic MFA

The in-use stock is the cornerstone of the dynamic MFA. The in-use stock is the amount of the product or material in active use that can provide the economic output and service function for our daily work and lives (Chen and Graedel, 2015a, 2015b). The time-dependent effect and expansion of the in-use stock codetermine