Estimating and calibrating the amount of building-related construction and demolition waste in urban China

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Abstract

One side effect of the unprecedented urbanization in China is the large amount of building-related construction and demolition (C&D) waste generated during the process. It is an enigma why such statistics as C&D waste generation are absent from the literature in spite of their importance to devising sensible interventions to deal with the C&D waste related problems. This paper aims to estimate the amount of C&D waste at the country level. It does so by adopting a methodology utilizing national statistical data and the average amounts of waste generated at job sites. Furthermore, the estimation is undergone a thorough calibration against various independent sources before it can be accepted confidently. It is finally estimated that approximately 1.13 billion tons of C&D materials were generated in China during 2014, which has declined from a plateau of building activities and C&D waste generation in the early 2010s. The paper provides some useful references for devising appropriate C&D waste reduction, reuse, or recycling strategies. The paper also offers useful commentary on methodology to estimate C&D waste generation at an urban level, particularly in situations where data availability is erratic.

Keywords: Construction and demolition waste; Estimation; Calibration; Waste management;

Urbanization; China

Introduction

C&D waste is one of the major side effects of urbanization; it contributes significantly to environment degradation (Coelho et al., 2012, Lu and Yuan, 2010; Lu and Tam, 2013; Udawatta et al., 2015) and thus requires careful management. Much research effort has been paid to estimating the amount of C&D waste generation, as a starting point of construction waste management. For example, the U.S. Environmental Protection Agency (USEPA) (2009) estimated the amount of C&D waste to target materials for reduction, reuse, and recovery as part of its Resource Conservation Challenge. The old saying that 'you cannot improve what you cannot measure' offers a rationale for research conducted to estimate the amount of C&D waste. Likewise, Li et al. (2013) emphasized that information about C&D waste generation is a prerequisite to developing appropriate solutions for managing waste. They noted that studies of this kind can be divided into two categories: studies that determine an overall C&D waste generation total in a region and those that measure a C&D waste generation index at project sites. This paper focuses on the estimation of C&D waste generation at an urban level.

For some urban areas (e.g. Australia, Europe, the UK, or Hong Kong) where C&D waste data has been systematically collected and released regularly, estimation of waste generation is unnecessary, unless it is to challenge or verify official statistics. However, contrasting to our orthodox wisdom, statistics on total C&D waste generation in many countries, including some developed economies, are not always readily available. For example, there seems no systematic publication of statistics on total C&D waste generation in the U.S. One has to refer to an *ad-hoc*, extant study by USEPA (2009), estimating that approximately 170 million tons of building-related C&D materials were generated in the U.S. during 2003. Likewise, there is no statistics on C&D materials in Japan continuously published by authorities. These estimations are particularly unavailable in developing countries, where building-related C&D waste is emerging as an urgent issue. In this paper, 'building' is both a noun to represent a physical structure and a gerund to describe the building activity.

Recently, building-related C&D waste in China has again come into the international media spotlight. In Shenzhen, a city in South China, the collapse of a huge pile of construction debris unlawfully disposal of in a former stone quarry toppled 33 buildings and trapped dozens of people (Buckley and Ramzy, 2015a). There was a quick estimation of C&D waste generation per annum by a media PhoenixTV to show the insufficiency of landfill space that is properly managed but other than this, no other statistics have been officially published in either Shenzhen or other urban areas in China, despite the fact that the *Administration of Urban Construction Garbage* was promulgated in 2005. Estimation of building-related C&D waste generation has long been due in China. Researchers have provided insights into the process of urban land conversion in China (Zhao and Webster, 2011). However, the externality effects of urban land conversion in terms of C&D waste generation, are under-researched. The few studies that do exist still cited an outdated approximate waste generation rate of 500-600 ton per 10,000 m^2 provided by Lu (1999) 15 years ago, who, without describing the methodology, used a simple rule-of-thumb (Lu et al., 2011). Guo (2009) reported that waste generation was around 100 million tons from new construction and 500 million tons from demolition.

The aim of this research is thus to estimate the C&D waste generation in China. Owing to erratic data availability, in particular data for public work projects such as roads, railways, bridges, utilities, piers, and dams, our estimate is confined to building-related C&D waste only. The rest of the paper is structured in four sections. Section 2 is a literature review of previous studies estimating C&D waste, with special consideration given to their methodologies. Section 3 describes the selected methodology, which is adapted from USEPA (2009) and Bergsdal et al. (2007). However, this research extends it by using estimation calibrations against various independent sources. Analyses and results are reported in Section 4, with due comment on data quality and the suitability of alternative proxies. In Section 5, the results are calibrated. In Section 6, the results are further discussed and the implications are explored. Conclusions are drawn in Section 7.

Literature review

Estimation of C&D waste generation at a regional level

Researchers estimated overall C&D waste generation amount in various regions. For example, Cochran et al. (2007) explored the accounting, generation, and composition of building-related C&D waste in Florida, US. Six specific categories of debris were examined: residential construction, non-residential construction, residential demolition, non-residential demolition, residential renovation, and non-residential renovation. As a result, Florida was estimated to generate approximately 3,750,000 metric tons of building-related C&D debris in 2000 (Cochran et al., 2007). Bergsdal et al. (2007) projected C&D waste in Norway using a methodology that can be described in three steps. First is to estimate the amount of activities (m^2/year) of (1) construction, (2) renovation, and (3) demolition of buildings. Second step is to determine the specific waste generation factor (kg/m^2) for different fractions of solid waste related to each type of activity. The third step is to calculate overall waste generation projection (tons/year) of materials outflow from the building stock. In an attempt to estimate the quantities of construction waste generated in Thailand, Kofoworola and Gheewala (2009) multiplied the quantity of different types of building activity with waste generation rates (e.g. new residential building activity generated 21.38 kg/m^2 of waste and new non-residential building generated 18.99 kg/m^2). Similar studies include Hsiao et al. (2002), Reinhart et al. (2003), and Müller (2006).

Estimation of overall C&D waste generation was also conducted by national environmental authorities. The USEPA (1998; 2009) conducted two studies to estimate building-related C&D waste generation in the U.S. in 1996, and 2003 respectively. It adopted a method similar to Bergsdal et al. (2007). C&D debris is produced when new structures are built and when existing structures are renovated or demolished. Here, structures include all residential and non-residential buildings as well as public works projects, such as streets and highways, bridges, piers and dams. Given the limited data availability, only building-related C&D materials were estimated by USEPA (2009). These were classified into three activities: construction, demolition, and renovation, in residential and non-residential buildings respectively, making six categories of waste to be estimated (USEPA, 2009). The methodology utilized national statistical data on the amount of construction, renovation, and demolition activities in the U.S. and average amounts of waste generated at job sites in estimation. The latter were calibrated from various job site C&D materials surveys conducted by other parities, e.g. the National Association of Home Builders (NAHB) (1997), and METRO (Portland Oregon).

Estimation of C&D waste generation on a project level

Estimating C&D waste generation on a project level also attracted considerable research interests (e.g. Skoyles, 1976; Bossink and Brouwers, 1996; Tam et al., 2007; Poon et al., 2004; Lin, 2006; Lu et al., 2011; Li et al., 2013). Lu et al. (2011) conducted a review of the research by focusing on the waste generation rate (WGR) as an index for measuring C&D waste generation on a project level. In addition to its use in benchmarking construction waste management (CWM) practices, raising people’s awareness of CWM, and assisting contractors in developing effective strategies, WGR can also help estimate the overall C&D waste generation on a regional level. Cheng and Ma (2013) made a summary of existing methods for C&D waste estimation, including the ones based on the constructed area, on the Global Index, the component index in a building, in a region through material stocks and flows, on quantities obtained from related databases, according to physical layout forms, or on accounting tools.

Chinese researchers started to investigate C&D waste generation on a project level, which is critical for the estimation of the amount of building-related C&D waste in urban level as a whole. For example, Lu et al. (2011) investigated WGRs by conducting on-site waste sorting and weighing in four construction projects in Shenzhen, South China. The results revealed that WGRs ranged from 3.275 to 8.791 kg/m^2, and that miscellaneous waste, timber for formwork and falsework and concrete were the three largest components amongst generated waste (Lu et al., 2011). Li et al. (2013) developed a construction waste generation index model for quantifying waste generation per gross floor area (GFA) in China, based on the mass-balance principle for building construction. A newly constructed residential building in Shenzhen was used as a case study to illustrate the model, and the waste generation of this case was 40.7kg/m^2. Of that amount, concrete represented 43.5%, timber formwork 18.7%, steel bar 9.8%, brick and block 8.4%, mortar 8.4% and tile 1.2% (Li et al., 2013). Ding and Xiao (2014) estimated that approximately 13.71 million tons of building-related C&D waste was generated in 2012 in Shanghai, of which more than 80% of this C&D waste was concrete, bricks and blocks. The research opened a window through which C&D waste generation totals in China can be estimated.

Methods

In order to estimate the amount of building-related C&D waste generation, Eq. (1) is established for guiding data collection and waste generation estimation.

$$W_t = W_c + W_d + W_r = AC \times WGR_c + AD \times WGR_d + AR \times WGR_r \qquad (1)$$

Where W_t is the estimated total amount of building-related C&D waste generation, W_c is the waste generated from new construction of buildings, W_d is the waste generated from demolition of buildings, and W_r is the waste generated from renovation of buildings, AC is total floor area of building under construction (m^2), and WGR_c is waste generation rate (ton/m^2) in building construction; AD is the total floor area of demolished building (m^2), and WGR_d is waste generation rate (ton/m^2) in building demolition; AR is total floor area of building under renovation (m^2), and WGR_r is waste generation rate (ton/m^2) in building renovation.

The method is similar to the ones adopted by Bergsdal et al. (2007) and USEPA (2009). A considerable amount of effort was paid by USEPA (2009) to determine total floor area (m^2) of residential construction, renovation, and demolition. This was because the U.S. Census Bureau, similar to its counterparts in Australia and the UK, only releases the number, not area, of home construction. In China, homes and non-residential buildings are sold by floor areas (m^2). They are mostly high-rise buildings, predominantly adopting a composite structure of steel and concrete using cast in-situ technologies, although low-waste technologies such as full steel structures, and prefabrication have been adopted by some landmark office buildings and exemplar residential buildings respectively. Because of the similarities in construction between the two sectors, residential and non-residential buildings are combined together in estimating the total amount of building-related C&D waste in China. It is noted that the similar approach was also adopted in Phoenix TV's estimation as mentioned above.

The research methods provide an analytical process for estimating the building-related C&D waste generation in China with limited information. Another perpetual burden is to reasonably sample in China, which is well known for her considerable regional imbalance between the Eastern Seaboard urban spaces and those in the inner parts of China. The intention of the Central Government is to have a set of uniform laws and regulations governing construction activities and their environment issues. However, different regions have different construction management capacities, technologies, productivity, and in turn C&D waste generation levels. The problem of estimating the amount of building-related C&D waste generation at the country level is converted to estimating the waste generation in each characteristics zones. This conversion is especially important as waste generation reduced by different construction practices vary in a big country such as China. Assuming there are *m* zones with similar characteristics in each corresponding zone, and *AC* (total floor area of building under construction), *AD* (the total floor area of demolished building), and *AR* (total floor area of building under renovation) can be found in Formulas (2), (3), and (4), respectively:

$$AC=\{AC_1, AC_2, AC_3,\ldots AC_m\} \qquad \text{Formula (2)}$$

$$AD=\{AD_1, AD_2, AD_3,\ldots AD_m\} \qquad \text{Formula (3)}$$

$AR=\{AR_1, AR_2, AR_3, \ldots AR_m\}$ Formula (4)

Their waste generation rates (WGRs) can be found in Formulas (5), (6), and (7), respectively:

$WGR_c=\{WGR_{c1},WGR_{c2},WGR_{c3},\ldots WGR_{cm}\}$ Formula (5)

$WGR_d=\{WGR_{d1},WGR_{d2},WGR_{d3},\ldots WGR_{dm}\}$ Formula (6)

$WGR_r=\{WGR_{r1},WGR_{r2},WGR_{r3},\ldots WGR_{rm}\}$ Formula (7)

The building-related C&D waste generation at the country level can therefore be estimated through Formula (8), which is a detailed version of Formula (1) by decomposing it into different zones:

$$W_t=\sum_{i=1}^{i=m} AC_i \times WGR_{ci} + \sum_{i=1}^{i=m} AD_i \times WGR_{di} + \sum_{i=1}^{i=m} AR_i \times WGR_{ri}$$

Formula (8)

Ideally, field study to all these regions is necessary for identifying the WGRs. However, in reality, it is difficult to do so with limited funding and time. This study mainly utilizes secondary data from other similar research. Bearing in mind the regional imbalance, the researchers however excluded the apparent outliers of the secondary data. The process relies heavily on the researchers' discretion on the subject matter but inter-rater reliability was tested in the process, i.e. three authors of the paper examined the results against the data sources independently and consensus should be reached, otherwise, average summation was adopted to reduce potential variations.

Estimation is inherently inexact; the effort to estimate is to continuously improve the results towards *approaching* a reality, although 'reality' itself is subject to a long history of inconclusive philosophical debate, e.g. ontology vs. epistemology. It is thus critical to calibrate the estimate results against various independent data sources so that the results can be accepted with an appropriate degree of confidence. In this study, considerable efforts have been paid to the calibrations of all the variables and C&D waste generation totals against various available first or secondary data sources. Likewise, during the calibration process, based on the researchers' discretion, some apparent outliers were excluded as the edges forming a reasonable range. If an estimate falls within the range, it can be accepted. Otherwise, we revisited both the estimate and the range to try determine the acceptance of the results.

Analyses and results

W_c, AC, and WGR_c

China Statistical Yearbook on Construction publishes annual construction data, including total building construction floor areas (CFA) under construction and CFA completed. Data for the past eight years ranging from 2007 to 2014 was retrieved and tabulated (Table 1). The fact that China publishes overall building CFA confirms our above consideration to combine residential and non-residential buildings in estimating their waste generation. Following the method adopted by Niu (2008), we define *AC* as *CFA under construction*. For waste generation parameters, we use the waste generation rate for new construction reported by Li et al. (2013), which is 40 kg/m^2. We use it as a constant within the time frame by seeing no significant C&D waste management and technologies introduced during the period. The total waste generated from construction of buildings in these years is estimated and shown in Table 1. Taking year 2014 as an example, it was estimated as $Wc = AC \times WGRc$= 1355559.65×10000m^2×40.7kg/m^2=551,712,778 tons.

Table 1 Building CFA under construction, CFA completed, and estimated waste generation from new construction in China (2007-2014)

Year	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
Building CFA under construction (10000m^2)	548542.04	632260.99	754189.40	844056.90	1035518.88	1167238.42	1336287.60	1355559.65
Building CFA completed (10000m^2)	238425.31	260306.98	302116.53	278564.54	329073.26	335503.55	349895.79	355068.39
Estimated construction waste generation (tons)	223,256,610	257,330,223	306,955,086	343,531,158	421,456,184	475,066,037	543,869,053	551,712,778

Data source: NBS of China (2008; 2009; 2010; 2011; 2012; 2013; 2014; 2015)

W_d, *AD*, and WGR_d

There are a large number of demolition activities in China. With a considerable portion of new buildings being built on the sites of demolished buildings, this has given rise to not only environment and conservation concerns but also widespread social discontent. Qiu (2010), ex-Vice Minister of the MOHURD, China, said that new buildings are typically demolished after 25-30 years even though the designed service life is 50 years or longer. However, except for Shanghai, there was no national or provincial statistical data published to report the scale of building demolition (See Table 2). On the other hand, there is data with regards to CFA completed, or CFA under construction of buildings and other economic indicators (e.g. GDP, construction output) at the national level (See Table 3). Research effort should be devoted to estimating the total demolition activities at urban level in China using the limited data available.

Table 2 Building demolition, GDP, Construction total output, CFA under construction and CFA completed in Shanghai (2007-2014)

Year	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
Overall demolition floor areas (10000m^2)	825.00	1028.53	927.63	585.70	333.83	219.42	159.57	118.58
GDP (100000000RMB)	12494.01	14069.87	15046.45	17165.98	19195.69	20181.72	21818.15	23567.70
construction total output (100000000RMB)	2524.18	3245.77	3830.53	4300.19	4586.28	4843.44	5102.84	5499.94
Building CFA under construction (10000m^2)	16040.50	18055.00	19069.90	22996.81	24885.79	27961.55	29148.65	34994.68
Building CFA completed (10000m^2)	6090.22	5723.90	5719.93	6217.15	5984.74	6476.07	6274.25	7580.77

Data source: Shanghai Statistical Bureau [SSB] (2008; 2009; 2010; 2011; 2012; 2013; 2014; 2015)

Table 3 GDP, Construction total output, CFA under construction and CFA completed in China (2007-2014)

Year	2007	2008	2009	2010	2011	2012	2013	2014
GDP (100000000RMB)	268019.4	316751.7	345629.2	408903	484123.5	534123	588018.8	636138.7
construction total output (100000000RMB)	51043.71	62036.81	76807.74	96031.13	117059.65	137217.86	159312.95	176713.42
Building CFA under construction (10000m^2)	482005.5	530518.6	588593.9	708023.5	851828.1	986427.5	1132002.9	1249826.3
Building CFA completed (10000m^2)	203992.7	223592	245401.6	277450.2	316429.3	358736.2	401520.9	423357.3

Data source: China Statistical Yearbook (2008; 2009; 2010; 2011; 2012; 2013; 2014; 2015)

It is unnecessary that all the demolition areas are developed to new buildings immediately; technical issues (e.g. contaminated site, or unclear site geotechnical conditions to be surveyed) and institutional bureaucracies (e.g. planning control) that may delay the redevelopment of the areas. New design of buildings is often redeveloped with higher plot ratios so the CFA under construction and completed is normally larger than the demolition areas, let alone new buildings are also built on lands supplied elsewhere. It is also not uncommon that developers may expedite or slow down the redevelopment of the demolition sites, depending on the market conditions. However, demolition of buildings in a particular year is closely related to the determinant factors as just mentioned. The difficulty is to ascertain the exact algorithms that can model the demolition areas based on the determinant factors in the whole country, as there is no public data available to do so.

Without knowing the exact algorithms, an alternative method is to estimate the demolition areas in the whole country using the data in Shanghai by assuming that the determinant factors in Shanghai will play the similar, if not the same, roles in the whole country. The percentage of demolition areas in Shanghai against those in the whole country should be similar to the percentage of determinant factors (e.g. GDP, construction total output, CFA under construction, and CFA completed) in Shanghai against those at the country level. Except for the regional difference as a potential caveat, this assumption is optimal as there is no public data of demolition areas except for that of Shanghai. Within this context, the rule of thumb for estimating the demolition areas in China can be demonstrated in the following formula:

$$D_{it} = DS_{it} \times F_{it} / FS_{it}$$

Where D_{it} is the estimated demolition areas at the country level in a particular year *t* based on the *i*th determinant factor, DS_{it} is the published demolition areas of Shanghai in a particular year *t*, F_{it} is the published data of selected determinant factor of China in a particular year *t*, FS_{it} is the published data of selected determinant factor of Shanghai in a particular year *t*, *i* stands for the determinant factor used for forecast, 1 denotes GDP, 2 denotes construction total output, 3 denotes CFA under construction, and 4 denotes CFA completed.

Table 4 Estimated overall demolition areas and demolition waste in China (2007-2014) (unit: 10000 m^2)

Year	2007	2008	2009	2010	2011	2012	2013	2014
Forecast based on GDP	17697.76	23155.06	21308.42	13951.69	8419.34	5807.10	4300.56	3200.71
Forecast based on construction total output	16683.07	19658.42	18600.34	13079.76	8520.64	6216.31	4981.85	3809.98
Forecast based on CFA under construction	24790.66	30221.78	28631.37	18032.47	11426.83	7740.70	6196.98	4235.06
Forecast based on CFA completed	27633.48	40177.34	39798.02	26137.79	17650.49	12154.58	10211.69	6622.24
Average estimated overall demolition area	21701.24	28303.15	27084.54	17800.43	11504.33	7979.67	6422.77	4467.00
Estimated demolition waste generation (tons)	259,670,527	338,667,002	324,085,480	212,994,605	137,657,361	95,482,337	76,852,939	53,450,782

Based on the data in Table 3 and the above formula, the demolition areas of China from 2007 to 2014 can be estimated and tabulated in Table 4. The estimate finally accepted is the average of the four forecasted results demonstrated in Table 4, as it is difficult to distinguish which one is better than another. Similar to the situation in Shanghai, one can notice that the demolition areas in China have declined from the plateau in the early 2010s. The reasons are many. It may attributed to the cool down of the overheated real estate market in China in recent years. With the increasing environment and conservation concerns as well as widespread social discontent, urban authorities are also more careful in considering redevelopment options instead of simply razing an area to build new facilities.

Zhu (2010) identified two approaches to estimate waste generation rates in demolition (WGR_d): (a) demolition site investigations, and (b) using the material balance principle. It is straightforward to measure WGR_d by measuring total waste generated and dividing by GFA of a demolished building. However, no previous research has been reported to measure WGR_d using this approach in China. Alternatively, the material balance principle estimates WGR_d by assuming that materials used in the construction of a building remain unchanged during its service life, and largely becoming waste after demolition. Zhu (2010) converted the materials into weight and estimated a WGR_d for multi-story masonry structure buildings, multi-story building with shops, and multi-story framework structure buildings: respectively, 1263.9kg/m^2, 1198.1kg/m^2, and 1052.9kg/m^2 (Zhu, 2010), after deducting the weight of steel that will be fully recycled in reality. By comparison, in a study by Chen (2007), waste generation rates measured using an on-site method were estimated as Masonry structure (1321.7kg/m^2), Steel concrete structure (1755.1 kg/m^2), Brick and wood structure (905.3 kg/m^2), and Steel structure (878.9 kg/m^2). It can be seen that the results from Zhu (2010) and Chen (2007) are largely consistent. In our study we adopt an averaged set of *WGR* from the two sources: Zhu (2010) and Chen (2007) as the WGR_d for estimating overall demolition waste in China. That is:

$$WGR_d = (1263.9+1198.1+1052.9+1321.7+1755.1+905.3+878.9)/7=1,196.57 \text{ kg/m}^2$$

Using the WGR and the estimated demolition areas, demolition waste in China over the past years was calculated and tabulated in the last row of Table 4. For example, the overall demolition waste in whole China in 2014 is estimated as:

$$W_d = DV \times WGR_d = 4467\times 10,000\text{m}^2 \times 1,196.57 \text{ kg/m}^2 = 53,450,782 \text{ tons}$$

W_r, AR, and WGR_r

Renovation is defined by USEPA (2009) as improvements and repairs to existing buildings. It generates C&D wastes as old materials are removed and new materials added. C&D waste from building renovation is less regulated and under-researched. Only recently, in some major cities (e.g. Shanghai, Beijing), is it regulated that homeowners should open a billing account in the facilities management (FM) department of an estate before any renovation can be started. For example, the Xi'an Government regulates that this billing account has a deposit of RMB 2, 000 for a home CFA smaller than 100m^2; RMB 2, 500 for a home CFA between 100m^2 and 150m^2; and 3,000 for a home CFA larger than 150m^2. The FM department serves as a focal point for the estate whereby renovation waste can be managed, e.g. opening a designated area for temporary waste storage, preventing illegal dumping, and liaising with third-party services for waste disposal. While such systems might be a potentially good source of data for waste modeling, the practice in Xi'an, as an example, is immature and loosely enforced.

One more viable approach is to use building CFA completed (See Table 1) as a proxy to estimate renovation activities in new buildings. This echoes Zhu's (2010) method. In this case, the area of buildings under renovation is 4,233,573,000m^2 in year 2014. The challenge is to determine the annual rate of renovation activities in existing buildings in China. Various sources reported that renovation takes place every 6-10 years in hotels, offices, and other non-residential buildings, and every 10 years in private residential buildings (e.g. Huang, 2011). But it is extremely difficult to find the renovated floor area of existing buildings in China. Thus, waste generation in renovation of existing buildings is not considered in this study.

In recent years, several local governments (e.g. Luoyang, and Tengzhou) have started to publish guidelines on the calculation of construction waste generation in new construction, demolition and renovation. Although they rarely specified the data sources, they tended to adopt two rule-of-thumb estimates of renovation waste: 100 kg/m^2 for a home CFA smaller than 160m, and 150 kg/m^2 for a home CFA larger than 161m^2. In our study, we adopt the average of these values: 125kg/m^2 as the waste generation rate in building renovation (WGR_r). The overall building renovation waste generated is estimated and tabulated in Table 5. Taking the whole China in 2014 as an example, it is estimated that the overall waste generated from building renovation activities is

$W_r = AR \times WGR_r =$ 4,233,573,000 m$^2 \times$ 125 kg/m^2 = 529,196,625 tons.

Table 5 Overall renovation GFA and estimated renovation waste in China (2007-2014)

Year	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
Building CFA completed (10000m^2)	203992.7	223592	245401.6	277450.2	316429.3	358736.2	401520.9	423357.3

Estimated renovation waste generation (tons)	254,990,875	279,490,000	306,752,000	346,812,750	395,536,625	448,420,250	501,901,125	529,196,625

Calibration

The estimate needs to be calibrated against as wide a range of sources as possible. Proxies from various sources have been adopted to approximate critical variables in the estimation. There is no lack of estimates of this kind in the literature, but most estimates cite similar sources without proper substantiation and/or explanation of data quality and method. Tables 6 to 9 list the principal sources of estimates of total construction waste in China and/or component variables.

Total floor area of new building construction

For new building construction, developers have to submit reports for approval by the government, which is thus able to collate relatively good statistics. *Chinese Statistics Yearbooks* and *China Statistical Yearbook on Construction* have continuously published building CFA under construction and completed, for more than ten years. There is little controversy in accepting this source as reference for calculating total building construction volume. Therefore, 'building CFA under construction' can be confidently used as the estimate of total new building construction. In contrast, the estimate in Table 6 made by Qiu (2010) is a rough one, which is surprisingly inconsistent with the official statistics.

Waste generation rate in new building construction (WGR_c)

By converting the estimated waste generation rates to a uniform unit of kg/m^2, a range of values for calibrating WGRc can be derived (Table 6). At one end of the range are the estimates by Lu (1999), and Qiu (2010), which assume that 50-60kg waste is generated by constructing every m^2 of CFA. A similar figure is used by the Shenzhen Construction Norm, which suggests a total WGR of 50.4kg/m^2 in new building construction. The three rates are largely based on outdated norms, and we therefore reject them. At the other end, is the estimate used by Lu et al. (2011), giving a WGR of 3.275 to 8.791 kg/m^2. Their research focused on a very limited construction stage in a confined floor area, and thus the WGR is deemed too low to reflect the whole construction cycle. Instead, our study adopts the more up-to-date WGR of 40.7kg/m^2 given by Li et al. (2013), derived through quantifying waste generation based on the material balance principle.

Table 6 Alternative data sources for estimating construction waste generation by new construction in China

Variables	Descriptions	Sources
Total building construction volume	Every year there is an amount of about 2 billion m^2 floor areas built, almost consumed 40% of the world's cement and steel.	Qiu (2010)
WGR_c	An approximate waste generation rate of 500-600 tons per 10,000 m^2.	Lu (1999)
	A rough estimation shows that 500-600 tons of construction waste will be generated in producing every 10,000m^2 construction floor areas in mansion, case in-situ, or framework structures.	Qiu (2010)
	The results revealed that WGRs ranged from 3.275 to 8.791 kg/m^2 and miscellaneous waste, timber for formwork and falsework, and concrete were the three largest components amongst the generated waste.	Lu et al. (2011)

Total floor area of building demolition

By converting the estimated total building demolition areas in Table 7 to a uniform unit of m^2, a range for calibrating total building demolition in China is derived. At one end of the range is 150 million m^2 from Niu (2008); and at the other, 1.6 billion m^2 from Qiu (2010). In the absence of a nation-wide summary of total building demolition activity in China, we make an estimate using a rule-of-thumb formula, largely based on Shanghai data. Our estimates (see Table 4) fall within the range and are closer to the estimate given by Niu (2008). However, it is noticed that the total demolition areas has declined from a plateau in early 2010s.

Table 7 Alternative data sources for estimating construction waste generation by building demolition in China

Variables	Descriptions	Sources
Total building demolition volume	Total demolition volume in a single year takes up around 40% of all the existing buildings in stock.	Qiu (2010)
	China witnesses the demolition of 3×10^7~ 4×10^7 m^2 of old buildings, generating hundreds of million tons of demolition waste a year.	Zhu (2010)
	In our country, there are about 40 billion m^2 gross floor areas in stock. Currently, demolished buildings from urban renewal are about 150 million m^2 a year.	Niu (2008)
WGR_d	A rough estimation shows that 7,000-12,000 tons of waste will be generated in demolishing every 10,000m^2 construction floor areas of old buildings.	Qiu (2010)

	Waste generation in demolition is around 1 ton/m^2. More specifically, more than 1 ton of waste will be generated in demolishing 1 m^2 of multi-stories masonry structure buildings, and 1.2 ton for multi-stories framework structure buildings.	Niu (2008)

Waste generation rate in building demolition (WGR_d)

By converting the estimates of waste generation in building demolition to a uniform unit of kg/m^2, a range for calibrating WGR_d can be derived. These are largely convergent and we confidently accept 1,196.57 kg/m^2 as the WGR_d in this study, given that it has been appropriately substantiated from multiple data sources. At this juncture, it can be seen that WGR_d is about 29 times WGR_c. This resonates with USEPA (2009), which reported that on a per building basis, demolition waste quantities are often 20 to 30 times as much as C&D material generated during construction.

Total floor area of building renovation

Wang et al. (2004) estimated total renovation area at about 600 million m^2 per annum, we have found no other source to help estimate building renovation floor area, Chen (2011) only reported renovation output in value (Yuan), which cannot be further converted to floor areas (m^2) as there is no universal unit cost for renovation in China (Table 8). Huang (2011) also reported renovation output in value (Yuan). The data quality for existing building renovation is particularly poor. Due to data quality, we have therefore decided not to include new building renovation activities in our overall estimate. The difficulty is resonated by USEPA (2009), which reported that estimating renovation activities has the highest level of uncertainty.

Table 8 Alternative data sources for estimating construction waste generation by building renovation in China

Variables	Descriptions	Sources
Total building renovation	According to the statistics, renovated areas reach to around 600 million m^2 per annum in recent years.	Wang et al. (2004)
	The construction renovation sector has developed rapidly over the past 3 decades, reaching an output of 2.1 trillion Yuan last year. We believe that public residential buildings, e.g. hotels, will be renovated every 6-8 years, while for regular resident buildings, they will be renovated every 10 years.	Chen (2011)
	In calculating the numbers of renovated homes and commercial use buildings, there is a ratio of 7/3 between the two.	Niu (2008)

WGR_r	For residential buildings, the WGR is around 0.1t/m^2, while this rate for shops or office buildings is around 0.15t/m²	Zhu (2010)
	Largely, 2 tons of C&D waste will be generated in renovating a residential flat.	Niu (2008)

Waste generation rate in building renovation (WGR_r)

By converting the descriptions of estimated waste generation in building renovation to a uniform unit of kg/m^2, a range for calibrating WGR_r can be derived. These are very divergent: from 20kg/m^2 to 100-150kg/m^2. This study adopts 125kg/m^2 as WGR_r for two reasons: (a) it well falls within the spectrum, and (b) it is used as a guideline by several local governments.

Total building-related C&D waste generation in China

As can be seen from Table 9, estimates of total building related C&D waste in China vary significantly from one author and source to another. The estimate of 1.13 billion tons waste generation in 2014 in this study diverges significantly from the prevailing view that total C&D waste generated is a few hundred millions but less than 1 billion tons (Guo, 2009; Niu, 2008; Cheng, 2012). Although our estimate sounds surprisingly high, it is supported by other sources, which apportion C&D waste at around 40% in total municipal solid waste (MSW) (e.g. Qiu, 2010; Huang, 2012; Li, 2008). It is generally agreed that MSW statistics are more reliable as they are the first to have been collected by environment protection departments. The percentage of 40% also seems reasonable in light of the fact that this number is about 29% in the USA (Rogoff and Williams, 1994), 20-30% in Australia (Craven et al., 1994), and 20-30% in Hong Kong (HKEPD, 2012), all of which have better management of their C&D waste. In short, we offer the estimate of 1.13 billion tons as the most reliable estimate of China’s annual C&D waste given available data in 2014. Table 10 summarizes the component parts of the estimates from 2007 to 2014.

Table 9 Alternative data sources for estimating total construction waste generation in China

Variables	**Descriptions**	**Sources**
Total building-related C&D waste in China	Waste generated is around 100 million tons from new construction and 500 million tons from demolition.	Guo (2009)
	Total building-related C&D waste in China was about 423 million tons in 2003, 509 million in 2004, 575 million in 2005, and 668 million in 2006.	Niu (2008)
	Construction waste takes up around 30-40% of total municipal solid waste in China.	Qiu (2010)

	Around 200 million tons of C&D waste are generated in demolishing old buildings, and 100 million from new construction buildings. We have 40 billion m^2 gross floor areas in stock, annual demolition areas will be around 400 million m^2, generating more than 600 million tons of C&D waste per year.	Cheng (2012)
	In 2011, the total municipal solid waste (MSW) is about 7 billion tons, amongst which total construction waste is about 2.1 billion to 2.8 billion tons.	Huang (2012)
	Every year, around 6 billion tons of MSW are generated, amongst which 2.4 billon tons are C&D waste, taking up around 40% of total MSW.	Li (2008)

Table 10 Estimated amount of building-related C&D waste generated in China from 2007 to 2014

Year		Construction	Demolition	Renovation	Totals
2007	Tons	223,256,610	259,670,527	254,990,875	737,918,012
	Percentage(%)	30.25	35.19	34.56	100
2008	Tons	257,330,223	338,667,002	279,490,000	875,487,225
	Percentage(%)	29.39	38.68	31.92	100
2009	Tons	306,955,086	324,085,480	306,752,000	937,792,566
	Percentage(%)	32.73	34.56	32.71	100
2010	Tons	343,531,158	212,994,605	346,812,750	903,338,513
	Percentage(%)	38.03	23.58	38.39	100
2011	Tons	421,456,184	137,657,361	395,536,625	954,650,170
	Percentage(%)	44.15	14.42	41.43	100
2012	Tons	475,066,037	95,482,337	448,420,250	1,018,968,624
	Percentage(%)	46.62	9.37	44.01	100
2013	Tons	543,869,053	76,852,939	501,901,125	1,122,623,117
	Percentage(%)	48.45	6.85	44.71	100
2014	Tons	551,712,778	53,450,782	529,196,625	1,134,360,185
	Percentage(%)	48.64	4.71	46.65	100

Discussion

Unlike the situation in developed countries where demolition is usually the smallest contributor of the three sub-sectors (Bergsdal et al., 2007), demolition was the largest waste-generating sector in China in early 2010s when urbanization has gained momentum and there was an over-heated real estate market around the country (Table 10). Currently, demolition of buildings in Chinese cities is usually closely related with or even driven by urban development (Lai et al., 2014). The rapid rate of urbanization is attributable to a shortening of the urban redevelopment cycle and unusually waste-intensive construction. On the other hand, this has been exacerbated in China by a unique distribution of built-up area (unique city morphology) that has its explanation in China's particular experience in transitioning from a centrally-planned land economy. Nevertheless, it is noticed that building demolition activities have decreased, and so the demolition waste generation, with the deepening of China's urbanization. From Table 10, it can be seen that the portion of the C&D waste from building renovation only is comparable to that of new building construction. It is envisaged that renovation of existing buildings will significantly increase with the improvement of household income in China. Dealing with renovation waste is a great challenge ahead for policy-makers, practitioners, environmentalists, and researchers.

The estimate of 1billion tons of C&D waste generated in a single and typical year may be overly high. Fortunately, a significant portion of the waste is the excavated soil or inert C&D waste that can be reused and/or recycled. For example, inert construction waste consisting of materials such as debris, rubble, earth, bitumen, and concrete, can be used for land reclamation, site formation, and aggregates given proper treatment (Lu and Yuan, 2013; Tam and Hao, 2014). This, however, will not take place automatically without the maturity of the recycling industry through more environmentally friendly ways (e.g. deconstruction, or recycling demolition concrete). A tragedy caused by the untreated construction debris has reported in Shenzhen, a city that is supposed to stand on the frontier in dealing with construction waste (Lu et al., 2011; Yuan in *Buckley and Ramzy*, 2015b). This reveals great scope for the development of new instruments to green the industry. While some of these may result in dead-weight economic loss to the sector as the price of making the industry cleaner, others will be found to create value from waste and thus internalize within the industry some of the massive externality costs of China's urbanization.

As shown in Bergsdal et al. (2007), USEPA (2009), and this paper, estimation of building-related C&D waste generation at a regional level is by no means rocket science. Rather, the difficulty lies in finding reliable data sources for estimating (a) construction and demolition activities, and (b) unit waste generation rates from individual job sites. This is particularly difficult in China, a country with unnegligible regional imbalance in terms of urbanization and consequently construction, renovation, and demolition activities. It is legitimate to use secondary data given the apparent difficulties for a first-hand data collection strategy to cover all types of building activities in all regions in China, even with a focus on urban areas; the data sources should be treated with cautious though. One of the unique contributions of this paper is to calibrate the estimation against various independent data sources so that the results can be accepted with an appropriate degree of confidence. The estimate can be utilized to raise people's awareness of CWM and to set up a baseline against which the effectiveness of future CWM initiatives can be benchmarked.

Conclusions

Considering the limitation of estimating C&D waste at the country level with limited information, a systematic analytical process has been introduced in this study. By adopting a methodology that utilizes national statistical data and average estimates of waste generated at job sites, this study attempts to estimate the amount of building-related construction and demolition waste in China. The results are further calibrated against various independent sources before it can be accepted. It was estimated that approximately 1.13 billion tons of building-related C&D materials were generated in China during 2014 without counting the amount from renovation of existing buildings. Demolition was the largest sector contributing to C&D waste generation, representing around 35% of the total waste generated in the early 2010s. However, after years' of fast development, demolition activities have decreased. Renovation of existing buildings, on the other hand, will significantly increase with the improvement of household income in China. Dealing with renovation waste is a great challenge ahead.

The results in a single and typical year may be overly high, but fortunately, a significant portion of the waste can be reduced, reused, or recycled. This reveals great challenges but also prospects for the sustainable development of a green construction industry. Accurate measurements of C&D waste are critical, but generally speaking, efforts to improving the measurements are currently hampered by a general lack of data. Therefore, it should be recognized that the estimates have some level of uncertainty, and the results should be viewed in that light. Nevertheless, it is believed that the estimates contained in this paper reflect the best data currently available.

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