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Demolition waste generation and recycling potentials in a rapidly developing flagship megacity of South China: Prospective scenarios and implications

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HIGHLIGHTS

- Advanced methods to quantify demolition waste in regional level were developed.
- Demolition waste generation rates that considered multi type factors were surveyed.
- The recycling potentials of demolition waste subjected to two scenarios were evaluated.
- This approach is promising to be applied to other megacities and across China.

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ABSTRACT

China's construction industry is huge and widespread. Massive construction, particularly the large-scale urban renewable activities in megacities, inevitably causes billions of tons of construction and demolition waste, and arouses great environmental concerns, which have not been well documented. The need for accurate data and informed analyses and further policy making are therefore paramount. Case studies of a rapidly developing flagship megacity, Shenzhen city in South China, in-depth surveys on construction and demolition sites, recyclers and government department shave been conducted to obtain fundamental information about demolition waste from its generation to disposal. Next, advanced methods to estimate and extrapolate the generation, flows and utilization options of demolition waste have been created. Results show that approximately 14 million tons of demolition waste has been produced in Shenzhen city annually from 2010 to 2015 and will trend upward in near future. The recycling potential based on current utilization options is valued at around 1.02 billion USD in 2015 and this number could soar to 1.38 billion USD if recycling rates are maximized. To summarize, the findings of this study provide quantitative documentation for generators, recyclers and the government to take responsibility for sound management of demolition waste, including waste collection, transportation, utilization options and landfill planning. This approach could give insight into the quantification of demolition waste if applied to other megacities and across China.

1. Introduction

Throughout the world, a large quantity of construction and demolition (C&D) waste has been produced from construction, demolition and reconstruction sites [1–3], since ongoing urbanization prompted massive urban development and renovation activities. It is reported that approximately one billion tons C&D waste was generated in China in 2014, of which only5% had been recycled [4].

If looking at the sources of C&D waste generation, demolition activities contributes over 70%, and the waste generation amount per unit gross of floor area (m^2) at a demolition site is more than 50 times of that of a new construction site [5,6]. The composition of demolition waste (DW) consists mainly of concrete, mortar, brick, metal, timber, plastic, etc. [7–9]. Although the majority of these wastes are materials could be reused and recycled, they were often disposed of by landfilling and dumping, triggering serious environmental impacts [10–13]. One of the most effective ways

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to reduce these impacts is to minimize the generation of C&D waste at the beginning of management [14,15], and then introduce a recycling method for processed C&D waste [16], thereby avoiding massive landfilling of waste, and preserving the capability of waste dumps [17]. Besides, if the recycling of C&D wastes in China were to rise to 90%, it is estimated that 600 billion Yuan could be saved directly [18].

With regard to the Shenzhen city (introduced in section 4.1), which is adjacent to Hong Kong in South China, like many other megacities in China, it has been experienced the rapid urban expansion. Large-scale urban renewable activities have become the major way to provide enough building space, but also resulted in massive DW. To collect these wastes, ten landfilling sites with the capacity of 10 million cubic meters for each, and six recycling facilities have been constructed over the last two decades. Recently, on-site process system has been introduced to recycle waste during the demolition activities. In this system, DW is initially crushed by a mobile crusher. The aggregate is then classified by sizes. Large sizes are between 30 and 50 mm, middle sizes fall into 10–30 mm and small sizes are less than 10 mm. These aggregates can be added to make recycled concrete, mortar and brick. This system could decrease the transportation cost of waste, thereby reducing the risk of illegal dumping and increasing the recycling rate [19]. Even though, the recycling rate has only reached up to around 40% which is far below the goal of achieving 90% by 2020, despite Shenzhen's being in a leading position in China for C&D waste management [20,21].

To improve the recycling rates and decrease the amount of DW that is transported into landfills in a particular city, the management of DW must be programmed. The first step towards the correct management of DW is to determine its generation and composition [22,23]. Once the generated amount and recycling potential are accurately projected, proper management plans could be arranged, including the number and size of recycling facilities and landfills needed. Besides, it is necessary to better understand the composition of DW, so as to improve its effective and efficient recycling.

However, there are two main barriers that hamper the projection of the generated amount and recycling potential of DW in particular region. First, there is a lack of regular statistics on the quantities of DW in most cities in China [24]. Consequently, the number of recycling facilities and landfills is insufficient in some cities while it is too great in other cities. Second, although there are a number of studies that estimate the quantity of C&D waste, ranging from the regional level to the project level, based on data from previous studies, regional data or relatively small sites surveys, this information cannot meet the standards of accuracy necessary to construct proper waste management schemes [25]. In addition, the data reporting on waste generation rates (WGRs) and compositions are heterogeneous across regions [1]. For example, the proportion of ceramics in DW in Spain is 42.3% [23], while it is only 1.2% in Portugal [26]. Obviously, those data could not be employed when planning recycling facilities and landfills in another region.

Therefore, how to establish an appropriate method to estimate the generation, flows and recycling potentials of DW, how to obtain reliable data for the projection, and how to provide feasible recommendations to improve the recycling rates and decrease landfilling have become urgent questions to answer. This study will firstly conduct a critical review of studies on estimating and predicting C&D waste generation and to identify opportunities and gaps. Secondly, an advanced approach to estimate the generation and flows of DW in Shenzhen city has been developed, as well as the utilization options and recycling potentials. Finally, the study provides recommendations for generators, recyclers and government departments to soundly manage DW, particularly applied to megacities and across China.

2. Systematic review of current studies on C&D waste generation

This section reviews the major studies to quantify C&D waste which appeared in international journals over the last 10 years. This review seeks to show the main issues discussed in these studies with respect to the proposed projection models, as well as to examine the reliability of data used. Three main topics have been reported, namely estimating C&D waste generation at the regional level, the project level and obtaining of WGRs (Table S1).

2.1. Non-Chinese studies

2.1.1. Projection of C&D waste generation in regional level

The first group of studies estimates C&D waste generation in a region by using one of three main methods. Eq. (1) was the most widely used model in the projection of C&D waste generated in a particular region [23,27–30].

$$W = A \times WGR \tag{1}$$

where W refers to the total weight of construction, renovation and DW generated in a region (unit: kg, t or m^3), A refers to the area of buildings been constructed, renovated or demolished in that region (unit: m^2), and WGR grefers to the average waste generation per building area during those activities (unit: t/m^2, kg/m^2 or m^3/m^2).

This method could be expressed in three steps: The first step is estimating the amount of activity involved in the construction, renovation, and demolition of buildings. This is followed by determining the specific waste generation factors for different fractions of solid waste related to each type of activity. Finally, the third step is calculating the overall waste generation out flowing from building stock. The following studies employed this method are considered here:

- The study conducted by Kartam et al. (2004), highlighted C&D waste generation two ways. The first one is a statistical analysis (comprehensive payload statistics based on the number of trucks arriving to controlled main landfills) and the second one is an estimation of the generated amounts based on an investigation of waste production activities and the waste handling systems. These two ways led to different results of waste generated amount in a region of Kuwait. In the first way, the annual amount of building wastes is about 3 million tons/year, while in the other way the total C&D waste production was estimated to be 1.6 million tons/year [27].
- In the US, Cochran et al. (2007) estimated waste generated in the construction, rehabilitation and demolition of buildings in Florida. The study was based on second hand data from several studies and took into account new estimation ranges employed the constructive technique [28]. Similarly, another study presented a materials flow analysis (MFA) approach for estimating C&D waste generation and composition on a national level by using historical data [30].
- In Norway, a study employed this principle of estimation more extensively [29]. The study applied the information obtained from Statistics Norway (1998) and developed a simple model of stocks and flows of buildings and materials to project the generation of C&D waste. To make the results more robust, Monte Carlo simulation has been used in the calculations to account for uncertainties related to the input parameters.
- A Spanish study conducted by Lage et al. (2010) presented a procedure to ascertain the production and composition of C&D waste. The data were taken from Galician Statistics Institute, National Statistics Institute of Spain and the Spanish Ministry of Public Works. The method proposed in the study has

been applied to Galicia, one of Spain's autonomous communities, in which the quantity and composition of C&D waste have been estimated for the horizon year 2011 [23].

Also, a Cyprus study focused on DW conducted by Kourmpanis et al. (2008) employed Eq. (2) to project waste generation:

$$DW = ND \times ANF \times AS \times DWB \times D \tag{2}$$

where DW refersto the generated quantities of DW (ton); ND refersto the number of buildings that were demolished; ANF refersto the average number of floors per demolished building (1.3); AS refersto the average surface of building which is going to be demolished (130 m^2); DWB refers to the volume of the generated waste per 100 m^2 of surface of demolished building (80 m^3 per 100 m^2); and D is the density of generated waste (1.6 t/m^3) [31].

Apart from the above methods, in Portugal, DeMelo et al. (2011) estimated the C&D waste generated in the Lisbon Metropolitan Area in 2006 and 2007 based on construction activity and waste load movements. Theoretical references have been considered to provide an average C&D waste generation indicator (kg/m2) used in the study. The results revealed that in the municipality of Lisbon, 954 tons of C&D waste was produced per day [32].

2.1.2. Projection of the C&D waste generation in project level

The second group studies are the projection of C&D waste generated at the project level by using various models.

First, similar to projection of regional level, the method based on Eq. (1) above was also used as a tool to estimate the C&D waste produced from construction or demolition projects. In the Spanish study conducted by VilloriaSaez et al. (2012), it estimated the volume of C&D waste that expected to be generated in the target project, by multiplying the indicator value (m^3_{waste}/m^2_{bs}) and the total built surface (m^2_{bs}) [33].

Second, another method for projecting C&D waste generation at the project level was provided by Solís-Guzmán et al. (2009). This model first identifies the material items, and then multiplies the amounts of material items used in the project and the transformation coefficient of that, which is expressed by Eq. (3). In their study, a quantification model was developed by studying 100 dwelling projects in Spain, especially their bill of quantities. A case study was conducted to illustrate the usefulness of the model to estimate C&D waste volume in both new construction and demolition projects.

$$VAW_i = VAC_i \times CT_i = Q_i \times CC_i \times CT_i \tag{3}$$

where VAW_i refers to the Apparent Waste Volume for the waste item "i" in m^3/m^2. VAC_i refers to the coefficient for the transformation of VAC in VAW (dimensionless). CT_i refers to the Apparent Constructed Volume for the item "i" in m^3/m^2. i refers to the quantity of the item "i" in its specific unit (m, m^2, m^3, kg or unity)/m^2. refers to the conversion ratio of the amount of the item "i" in in m^3/Q_i specific unit [34].

Other studies based on this principle are classified as follows:

- Mercader-Moyano and Ramirez-de-Arellano-Agudo (2013) carried out a practical example on ten residential buildings in Seville, Spain, and then used a model similar to Eq. (3) to identify and quantify of the C&D waste generated in every m^2 construction work [35].
- Llatas. (2011) introduced another Spanish model to estimate C&D waste during the design stage in order to promote prevention and recovery. The types and quantities of C&D waste have been estimated according to EU guidelines [1].
- Similarly, Katz and Baum. (2011) sampled 10 new construction sites of residential buildings in Israel, and predicted the accumulation of CW based on field observations. The results show the total amount of waste from these sites was estimated at the figure of 0.2 m^3 per m^2. It indicated smaller amounts have been produced during the early stages of construction and increasing amounts were generated towards the end of the project [25].

There are also other methods to estimate the generation of C&D waste. For instance, in Hong Kong, Li and Zhang (2013) proposed a web-based CW estimation system (WCWES) which further incorporates the concepts of work breakdown structure, material quantity takeoff, material classification, material conversion ratios, material wastage levels, and the mass balance principle [36].

2.1.3. Obtaining the C&D waste generation rates

As the basis of projecting C&D waste generation, the generation indicators - namely the WGRs – have drawn a lot of attentions from researchers. Malia et al. (2013) examined previous international studies to obtain these indicators. In that study, the C&D waste generation rates were classified into six specific sectors: new residential construction, new non-residential construction, residential demolition, non-residential demolition, residential refurbishment, and non-residential refurbishment [26].

In Brazil, Parisi Kern et al. (2015) proposed a statistical model to determine the amount of waste generated in the construction of high-rise buildings by assessing the influence of design process and production system, these being mentioned as the major culprits behind the generation of waste. In this study, multiple regressions were used in the projection and the data was from a survey of eighteen residential buildings [37].

2.2. Chinese studies

As the projection of C&D waste generation became a significant research issue in China, several researchers studied this issue. These related papers are reviewed as follows:

- To get a quantitative cognition about concrete waste in all industry and building construction industry, Shi and Xu. (2006) estimated the quantity of concrete waste based on annual cement production and building areas respectively. The results indicated that the quantity of concrete waste reached 88 million tons in 2000 in China and will increase more than 8% annually in future [38].
- Ye et al. (2010) proposed a system dynamics model to serve as a decision support tool for estimating C&D waste generation. The dynamic model integrates all vital factors that affect C&D waste generation to describe C&D waste management and to analyze the best strategies for long-range planning under different scenarios [39].
- A method based on the principle of Eq. (1) above has been proposed to estimate the quantity and composition of building-related C&D waste in a fast developing region (Ding and Xiao, 2014). With the data collected from Shanghai statistical yearbook and the Building Construction Handbook from the 1st edition to the 5th edition (1980; 1988; 1997; 2003; 2012) and several previous studies, it concluded that approximately 13.71 million tons of C&D waste were produced in 2012 in Shanghai, and more than 80% of it was concrete, bricks and blocks [40].
- Wu et al. (2015c) proposed an innovative approach based on GIS to estimate waste generation trends, economic values and environmental effects of DW generated in a region. This research is innovative in terms of the systemization, visual representation and analysis of quantifying the DW flows [21].
Chinese researchers have also made efforts to obtain the WGRs in China.

- A study conducted by Lu et al. (2011) investigated WGRs by conducting on-site waste sorting and weighing in four ongoing construction projects in Shenzhen city in South China. The results revealed the WGRs range from 3.275 to 8.791 kg/m^2, and indicated miscellaneous waste, timber, and concrete are the three largest components amongst the generated waste [5].
- Another study focused on the WGRs of construction was conducted by Li et al. (2013). In the study, it first calculated the total DW by multiplying the purchased amount of material by the waste produced in every m^2 construction work, and then divides the gross floor area of the building. With a case study of a newly constructed residential building in Shenzhen, the WGR of this project was worked out as 40.7 kg/m^2 [2].

2.3. Summary

Based on the review, we have learned that there are a number of studies involved in the projection of C&D waste. The principle that calculates the waste generation by multiplying the WGRs by GFA of construction or demolition work has been widely used in both regional and project level. However, these studies ignored the fact that the WGRs could be affected by structure type and building type. In other words, the WGRs of brick-concrete structure and frame-shear structure are different. Thus, if the WGRs could be considered according to structure type and building type when projecting the waste generation, the results should be more accurate and reliable.

What is more, it was also found that one of the key factors to estimating the generation of C&D waste is determining WGRs. However, most of these studies are based on data from previous studies (In another word, data accuracy is questionable), statistical regional data or relatively small sites surveys, due to the difficulties involved in conducting survey on large-scale projects or regions. As a consequence, these data do not meet the standard of accuracy. Besides, the data reporting on WGRs and compositions of C&D waste are also heterogeneous. These wide-ranging results may be attributed to a number of different reasons such as the lack of reliable data sources, differences in economic power, city size, etc. Although some studies expressed the demolition WGRs in particular regions, studies based on information obtained first hand are still rare.

Given these shortcomings, this study will establish a useful advanced method that considered multi type factors to project generation of DW in a rapidly developing flagship megacity and provide a practical plan to obtain reliable generation data from demolition sites in the following section.

3. Method for estimating and extrapolating generation and utilization options

3.1. Model for estimating waste generation in a city in a single year

In order to estimate the quantity of DW produced in a city in a single year, it is necessary to calculate each type of DW first (see Eq. (4)), and then add all of them together (see Eq, (5)).

$$G_X = \sum_{IJ} GFA_{ij} \times WGR_{IJX} \tag{4}$$

where G_X refers to a generated amount of waste x that produced in the study region in the given year; GFA_{ij} refers to the gross floor area of building type i and structure type j demolished in the study region in the given year; WGR_{IJX} refers to the generation rates of waste x with the building type i and structure type j.

$$\mathrm{TG} = \sum_{x} G_X \tag{5}$$

where TG refers to the total generation amount of waste produced in the study region in the given year and G_X refers to the generated amount of waste x that produced in the study region in the given year.

3.2. Model for assessing the recycling potential value in a city in a given year

The first step to assess the recycling potential value in a city is calculating the recycling potential value of each type of DW (see Eq. (6)), followed by the summation of all types of DW (see Eq. (7)).

$$\mathrm{RPV}_x = G_X \times \mathrm{RPVI}_x \times R_X \tag{6}$$

where RPV_x refers to recycling potential value of waste x in the study region in the given year; G_X refers to generated amount of waste x that produced in the study region in the given year; RPVI_x refers to recycling potential value index of waste x; R_X refers to recycling rate of waste x.

$$\mathrm{TRPV} = \sum_{x} RPV_X \tag{7}$$

where TRPV refers to the total recycling potential value of waste produced in the study region in the given year and RPV_x refers to the recycling potential value of waste x in the study region in a given year.

3.3. Method for projecting waste generation using Gray theory

Since there is a lack of historic statistical data on the generation of DW in China, the normal extrapolation methodology is not suitable for projecting DW. Therefore, it is necessary to employ a projecting method that could bear the paucity of data and uncertainty of information. The Gray theory, first introduced by Deng (2002) [38], could work well under this condition, and it has been employed by Shi and Xu (2006) to forecast the building areas in China [38].

The essential work of Gray theory is to build a GM (1.1) model. To project waste generation using this method, one should comply with following steps (see Fig. 1):

(1) Building a GM (1.1) model

The first step is accumulating the original array to reduce the randomness of original data, followed by calculating the Develop Gray Parameter (a) and the Endogenous Control Gray Parameter (u), and finally build the projection model (see Eq. (8))

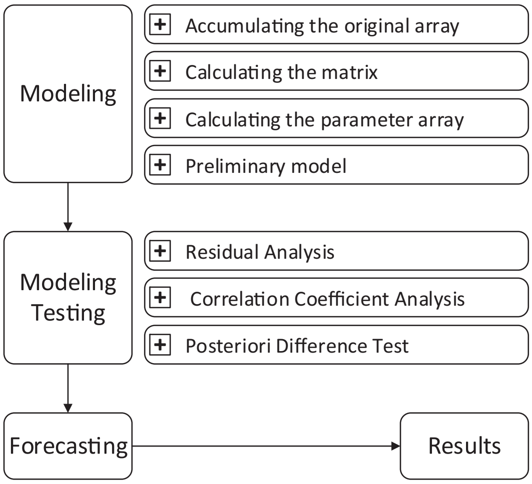


Fig. 1. The main process of GM (1.1) model.

$$\widehat{x}^{1}(k+1) = \left(X^{(0)}(1) - \frac{\mu}{\alpha}\right)e^{-ak} + \frac{\mu}{\alpha}(k = 0, 1, 2, \ldots, n) \tag{8}$$

(2) Model testing

The model testing includes Residual Analysis, Correlation Coefficient Analysis and Posteriori Difference Test. When the Correlation Coefficient is greater than 0.6, the Variance Ratio is less than 0.65, and the Small Error-Probability is over 0.70, then the model passes the exam.

For the details, please see supporting information.

4. Data obtaining, inventory and scenarios assumption

4.1. Case description

The Shenzhen city, with a population of 10 million people (2013), is situated in south China and border by Hong Kong (Longitude 113°46′ to 114°37′ E and Latitude 22°27′ to 22°52′ N), It is a fast growing metropolis covering an area of about 2000 kilo m^2, twice in New York city. It has rapidly developed since the1990 s when I was set as a special economic zone in China. In two short decades, more than half million of new buildings have been constructed and tens of thousands buildings have been demolished [42]. Consequently, the management of C&D waste has become one of the most urgent issues of city development. Therefore, a case study based on this metropolis may provide useful recommendations for the government and other waste management stake holders. The process and results could also provide good experience for other fast growing metropolises over the world.

Table 1
The distribution of samples.

Interviewees positions	Sample number	Building type	Sample number	Structure type	Sample number
CEO	9	Residential Building	32	Brick-concrete	50
Project Manager	28	Industrial Building	20	Frame	10
Technical Director	3	Commercial Building	15	Frame-shear	18
Engineer	30	Public Building	11		
Construction Supervision Engineer	8				

Note: The survey interviewed85 respondents, where the effective number of samples is 78.

4.2. Investigation for data obtaining

In this study, three kinds of data need be obtained, namely the composition and generation rate of DW of different building types and structure types, gross floor area of demolition works, and their recycling potential value index.

4.2.1. WGRs

There liability of data that has been employed in the projection has significantly influenced the results. Due to the reasons like the differences in economic development, city size, construction practices, and so on, the data reporting on WGRs and compositions of C&D waste in different regions are usually heterogeneous. Obviously, these wide-ranging results cannot be simply applied in projections in other regions. However, conducting a survey of large-scale projects or regions is a time-consuming and laborious process. Thus, a practical plan to obtain reliable data is worth introduction.

First of all, the number of samples should be sufficient and the measurement unit should be cited appropriately. For example, the sample size should be large enough to conduct a statistic analysis, and the measurement unit should be the unit common in the industry. In this study, the survey interviewed 85 respondents, where the effective number of samples is 78. Allof these projects involve a total demolition area of nearly half million m^2. The WGR (namely the total quantity of waste generated from per unit area of demolition work (1 m^2)) and the WGRs for each material were investigated. The unit presents kg/m^2.

Second, the interviewees should be selected carefully so each has a depth understanding of the management flows of waste from generation to final disposal and can provide reliable data (see Table 1). In this investigation, the interviewees are direct managers in charge of demolition projects or have been in charge of at least one demolition project in the study area. The interviewees primarily work for general constructors (GC), professional demolition companies (PDC) and/or construction supervision enterprises (CSE). The positions of respondents should be selected as well. Appropriate candidates should be project managers, technical directors, engineers, CEOs of PDCs, or construction supervision engineers.

Third, the samples should cover the majority of building types and structure types in the target region. For example, the building types in Shenzhen mainly include residential, industrial, commercial and public buildings, where the proportion of residential buildings is the largest, accounting for 41%, while industrial, commercial

Table 2
The WGRs of different structure types.

Waste type	Residential		Industrial			Commercial			Public		Overall
	Brick-concrete	Frame	Brick-concrete	Frame	Frame-shear	Brick-concrete	Frame	Frame-shear	Frame	Frame-shear	Mean
Steer	67.58	145.00	71.00	95.00	55.00	100.00	73.00	75.00	55.00	81.67	73.85
Aluminum	7.90	15.00	14.33	5.00	7.50	7.50	11.00	12.50	7.50	11.11	10.00
Copper	1.45	–	10.67	6.67	30.00	–	4.00	–	–	8.89	4.94
Concrete	641.13	925.00	664.67	573.33	475.00	900.00	565.00	675.00	625.00	702.78	660.13
Mortar	111.29	125.00	80.00	58.33	175.00	100.00	25.00	191.67	125.00	108.33	105.13
Brick/Block	279.03	450.00	263.33	350.00	250.00	350.00	330.00	283.33	250.00	283.33	287.18
Ceramic	159.68	125.00	65.00	150.00	150.00	200.00	155.00	154.17	175.00	133.33	139.10
Glass	7.74	3.00	3.90	9.17	7.75	4.13	9.70	7.92	12.50	4.17	6.66
Timber	31.61	20.00	40.00	26.67	20.00	20.00	24.00	20.00	20.00	37.78	31.03
Plastic	5.81	40.00	9.33	6.67	10.00	10.00	12.00	3.33	10.00	17.78	8.97
Insulation Materials	15.48	–	18.67	–	10.00	–	8.00	6.67	–	13.33	12.56
Mixed Fragments	21.77	25.00	7.13	26.67	25.00	12.50	26.00	30.00	25.00	29.44	20.67
Total	1350.48	1873.00	1248.03	1307.50	1215.25	1704.13	1242.70	1459.58	1305.00	1431.94	1360.22

Note: Data are rounded to the appropriate significant digits. Data may not add to totals shown.

and public buildings accounted for 26%, 19% and 14% respectively. For the structure types, there are mainly three types, namely brick-concrete, frame-shear wall and frame. Brick-concrete structures are the most common since current demolition projects in Shenzhen are of buildings that were built in 1980 s, and a large part of these are farm buildings. Details of the sample are shown in Table 1.

4.2.2. Gross floor area and recycling potential value index

The annual gross floor area (GFA) of demolition work in Shenzhen could be obtained from Urban Planning, Land & Resources Commission of Shenzhen Municipality. The recycling potential value indexes have been determined through inquiry of the recycling industry. Six major recycling companies in Shenzhen were included, namely Lvfar green technology corp., Shenzhenshi Huawei Green Building Material Co., Ltd., Shezhenshi Yongan Green Building material Co., Ltd., Shenzhenshi Huilidebang Green Building material Co., Ltd., Huaquan Green Co., Ltd, and Shenzhen Ding Hao Building Materials Co., Ltd. The values used are the mean values of the prices of recycled materials provided by the marketing managers of those six companies.

4.3. Data inventory

4.3.1. Composition and generation rates of DW

The results of the investigation show the major compositions of DW are metal (steer, aluminum and copper), concrete, mortar, brick/block, ceramic, glass, timber, plastic, insulation materials and some mixed fragments. The overall mean value in statistics is 1,360.22 kg/m^2.Among the compositions, concrete is the dominant part of DW since it is widely used in all the structure/building types, which bears the largest WGR with the mean value of 660.13 kg/m^2. The second largest contributor is brick/block waste (Mean: 287.18 kg/m^2), followed by ceramic and mortar waste, with the mean value of 139.10 kg/m^2 and 105.13 kg/m^2, respectively. The weight of these four kinds of inert waste accounts for 88% of total weight.

For different building types and structure types, the WGRs differ. The mean value of WGRs of frame residential buildings is the largest (1873.74 kg/m^2) among four kinds of types of buildings. The followers are brick-concrete commercial buildings (1704.13 kg/m^2) and frame-shear commercial buildings with the number of 1459.58 kg/m^2. In contrast, the WGRs of industrial buildings are much smaller than the residential buildings. This is mainly because residential buildings consist of more partition walls due to the division of function, and those walls are normally made by brick/block in old buildings. Contrarily, due to their larger space spans, fewer partition walls, and larger doors and windows, the total weight of industrial buildings is much lighter per square meter than other types of buildings having the same gross flow area. The details of general WGRs of DW in Shenzhen are shown in Table 2.

Table 3
GFA of demolition work in Shenzhen (2010–2015), unit: million m^2.

Building type	Structure type	2010	2011	2012	2013	2014	2015
Residential	Brick-concrete	2.77	0.42	1.64	1.95	4.67	2.24
	Frame	4.15	6.48	4.09	0.84	0.79	1.03
Industrial	Brick-concrete	1.33	0.31	0.36	0.86	0.63	0.60
	Frame	5.31	1.22	1.42	3.44	2.53	4.25
	Frame-shear	–	–	–	–	–	–
Commercial	Brick-concrete	–	0.06	–	–	–	–
	Frame	0.25	1.82	0.56	0.42	0.42	1.45
	Frame-shear	0.00	0.27	0.17	0.12	0.11	0.15
Public	Frame	0.30	0.08	–	0.35	–	–
	Frame-shear	–	–	–	–	–	0.24
Total		14.10	10.66	8.24	7.97	9.16	9.96

Note: Data from Urban Planning, Land & Resources Commission of Shenzhen Municipality.

4.3.2. Gross floor area of demolition work

According to data from Urban Planning, Land & Resources Commission of Shenzhen Municipality, the average annual gross floor area (GFA) of demolition work in Shenzhen (2010–2015) is 10.02 million m^2. It reveals that the largest contributor of demolition GFA are residential buildings, especially frame residential buildings demolished before 2012.Since the demolition works in Shenzhen are mainly in accordance with the planning of urban renewal, and the renewal emphasizes are heterogeneous, the distribution of GFA is changed during the period. The detail figures are shown in Table 3.

4.3.3. Recycling potential value index

The recycling potential value indexes for each waste material are shown in Table 4. These metal wastes are usually collected by special collecting companies and handled together with metal waste from household waste or industrial waste. The recycling values of them are quite high, like copper, which is valued at more than six thousand USD per ton. By comparison, the recycling value indexes of concrete, mortar, brick/block and ceramic are still low,

Table 4
The value index of recycling products.

Waste type	Recycling value index (USD/ t)	Remarks
Steer	314.60	Flow to the metal industry as the material to produce new metal products
Aluminum	1887.60	
Copper	6292.00	
Concrete	39.33	Recycled as the aggregate for concrete products (i.e. concrete, mortar and brick/block)
Mortar	39.33	
Brick/Block	39.33	
Ceramic	39.33	
Glass	157.30	Recycled as the materials to make new products (i.e. glass, timber and plastic)
Timber	314.60	
Plastic	1573.00	
Insulation Materials	–	Not recycled, but transported to sanitary landfill or C&D waste landfill
Mixed Fragments	–	

Note: The values used are the mean values of the prices of recycled materials provided by six companies. i.e. Lvfar green technology corp., Shenzhenshi Huawei Green Building Material Co., Ltd., Shezhenshi Yongan Green Building material Co., Ltd., Shenzhenshi Huilidebang Green Building material Co., Ltd., Huaquan Green Co., Ltd, and Shenzhen Ding Hao Building Materials Co., Ltd.

Table 5
Treatment and disposal scenarios of DW.

Waste type	Current situation	Maximum recycling rate situation	Landfill rate
Steer Aluminum Copper	90%	95%	1-recycling rate
Concrete Mortar Brick/Block Ceramic	40%	95%	1-recycling rate
Glass Timber Plastic	70%	95%	1-recycling rate
Insulation Materials Mixed Fragments	–	–	100%

which are valued at just less than 40 USD per ton when they were recycled as aggregate for concrete products. Because insulation materials and fixed fragments are hardly ever recycled and are usually disposed of in sanitary landfills or C&D waste landfills, their recycling value indexes cannot be estimated.

4.4. Recycling scenarios assumption

To examine the recycling value in the current situation and the recycling potential value under the maximum recycling rate situation, two scenarios for waste treatment and disposal were considered in this study (see Table 5). In the current situation, metal wastes were recycled at the rate of 90% since they have very high economic value and as does the mature recycling market for glass, timber and plastic. Concrete, mortar, brick/block and ceramic waste could be recycled to aggregate and their recycling potential has attracted the interest of government and recycling industry. The overall recycling rate in Shenzhen is about 40%.Theoretically, except for insulation materials and these mixed fragments, the majority of DW could be recycled at the rate of 95%. Thus the recycling rates under maximum recycling rate situation adopt this percentage. Accordingly, the remaining portions of DW were not recycled and were stated as the landfill rates.

5. Results and discussions

5.1. Composition and contribution of demolition waste

The results show that the annual average generated amount of demolition waste in Shenzhen city from 2010 to 2015 is about 13.6 million tons. Among the major compositions, concrete waste contributes the largest percentage at 49%, followed by brick/block and ceramic, which contribute 21% and 10% of total DW, respectively. Besides, the mortar waste also is a big part of DW and its amount is accounted 8%. Statistically, those four types of waste contribute 88% as a whole. In terms of volumes, the most difficult part of DW management is obviously the disposal of those four wastes. It also shows that there is a noticeable proportion of steel waste, which accounts for 5% of all waste. For the remaining compositions, although the proportions are far less than those waste discussed above, the environmental impacts of them also need to be concerned, since there are high environmentally risky heavy materials like Zn, CU, Cd and As (Esin and Cosgun, 2007) [10]. The annual average generation amount of DW generated in Shenzhen and its composition and contribution are shown in Fig. 2.

Since the WGRs of different building types and structure types are different, the distributions of generation of DW are also heterogeneous. The details are shown in Fig. 3.

5.2. Projection of demolition waste generation

Fig. 4 displays the projects that from 2016 to 2030 using the GM (1.1) model. About 14 million tons of DW was produced in 2015 and it will increases to about 40 million tons in 2030. Considering the common annual recycling capability of each recycling facility (one million tons per year), there is a need for 20 recycling facilities to be operated in Shenzhen city for the government to be secure to achieving a full recycling rate. The number of recycling facilities should increase along with the increasing generation of DW.

5.3. The demolition waste recycling potential value

The recycling potential value of DW is analyzed by comparing two scenarios set above (Fig. 5). For the same composition of DW, the recycling method is the same under two scenarios, which could explain the effects of increasing recycling rate without influence from other factors. Under the current situation, the average annual DW recycling potential value from 2010 to 2015 in Shenzhen is about 1.02 billion USD, and if the maximum recycling rate is imposed, the number would increase 35% and soar to 1.38 billion USD. It is noticeable that the annual gross develop product value with the whole construction industry in Shenzhen in past five years were about 30 billion USD, which implies that the recycling potential value of C&D waste accounts for around 5% of the total.

Among those wastes, the increase of concrete in the two scenarios is definitely the most significant, which rises from 104 million USD to 247 million USD (increased 2.4 times). The increasing rates of brick/block, mortar and ceramic are also doubled. However, the

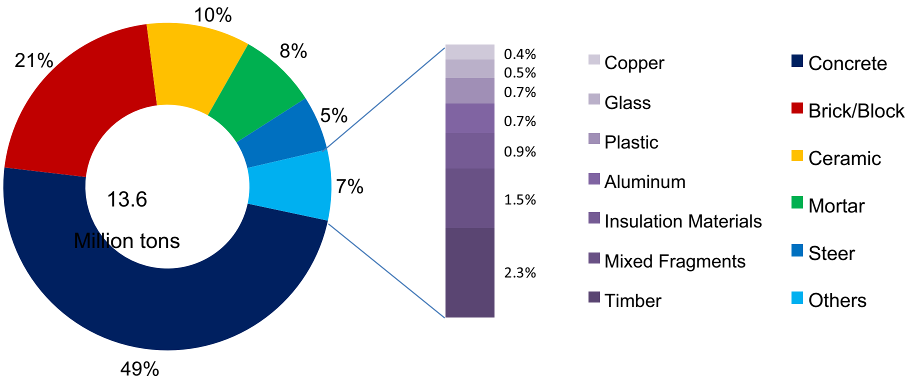
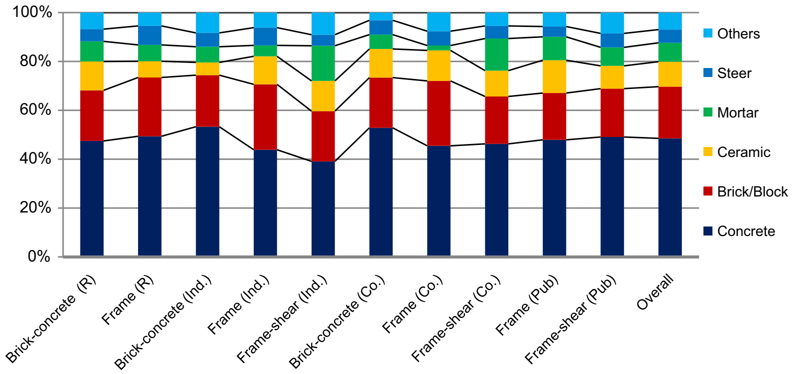


Fig. 2. Distribution of generation of DW in average.



Note: R refers to residential, Ind. refers to industrial, Co. refers commercial, Pub. refers to public.

Fig. 3. Distribution of generation of DW for different building type.

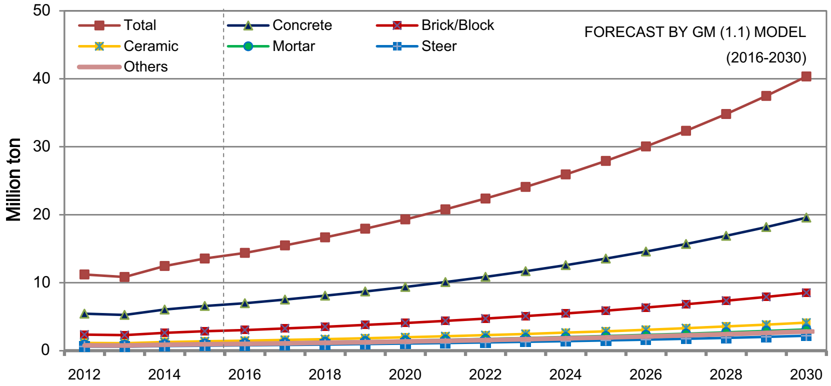


Fig. 4. Projection of DW generation in Shenzhen (2016–2030).

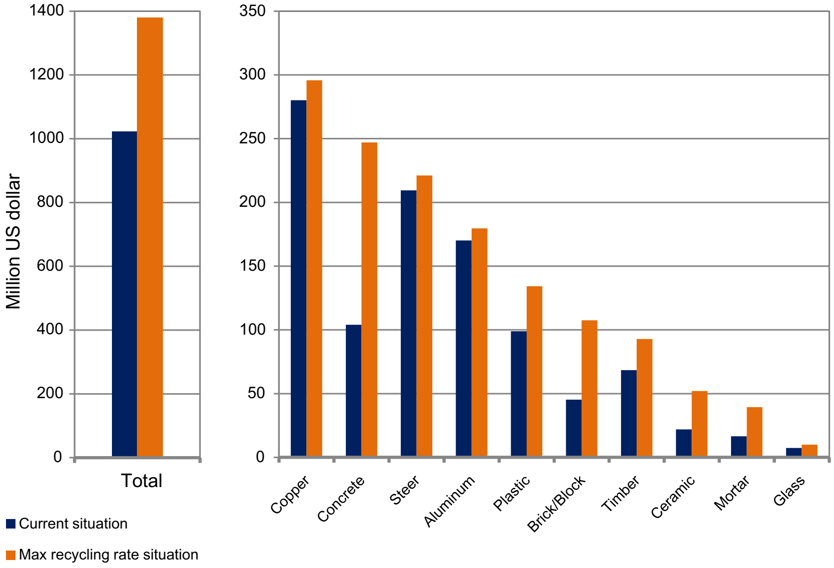
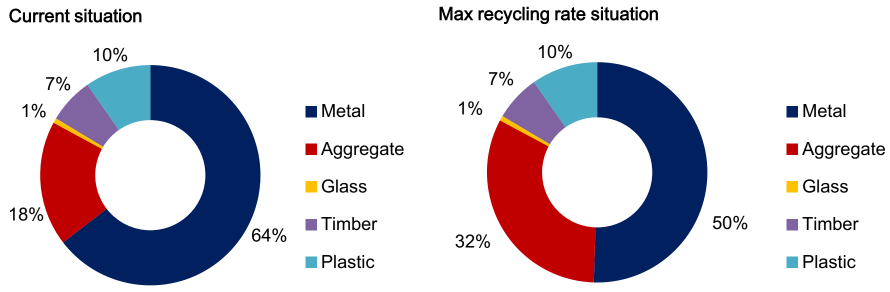


Fig. 5. Recycling potential values of DW in Shenzhen.

increasing potential of metal wastes is limited since the recycling rates of them are very high currently.

Fig. 6 shows the contribution of recycling value of DW under two scenarios. Under the current situation, metal wastes contribute the largest part, at 64%. When conducting the maximum recycling rate situation, this figure drops to 50%.In contrast, the contribution of those wastes that can be recycled as aggregate (i.e. concrete, brick/block, mortar and ceramic) will see an increasing trend. They rise from 18% to 32% when imposing the maximum recycling rate situation. However, the proportions of plastic, timber



Note: Aggregate includes concrete, brick/block, mortar and ceramic

Fig. 6. Contribution of recycling value of DW.

and glass remain the same under the different situations, since their recycling values are quite small when compared to metal and aggregate and their recycling rates are very high in current situation. Therefore, the recycling of concrete, brick/block, mortar and ceramics should be improved if the government or recycling industry secures a larger recycling market value.

6. Conclusions

The main contributions of this study are three fold. First, in terms of systemically review on papers relating to C&D waste generation and composition over the last ten years published in international journals, it finds that previous studies were mainly based on second hand data or small scale surveys, which do not meet the standards of accuracy of data. It is necessary, then, to conduct research on waste generation and its flows to secure more systemic and reliable data that could be used in C&D management planning, such as waste collection, transportation, recycling and landfill. The selection of survey samples and interviewees is significantly important in conducting large scale construction sites surveys since the selection directly determines the quality of data.

Secondly, advanced approaches for estimating and projecting the DW generation and its recycling potential in a fast growing metropolis have been provided, which could give insight into the quantification of DW if applied to other megacities and across China. The method employed could bear the paucity of data and uncertainty of information is extremely important, as the lack of historic statistical data on the generation of DW in China.

Finally, it works out the waste generation, composition and its recycling potential value in a real case, and provides the emphasis for DW management and recycling. Besides, the valuable data acquired in this study also provide opportunities for future research. The emphasis of C&D waste management should be put on the inert waste like concrete, brick/block, mortar and ceramic, because these four materials contribute nearly ninety percent of amount of all DW and have the largest increasing recycling potential.

This research is innovative in terms of the systemization, visual representation and analysis of quantifying the DW flows via a novel method. The findings on the generation trends, economic values and environmental effects provide valuable information for the future waste management exercises of various stakeholders such as government, industry and academy.

Future research opportunities exist to validate these findings in other regions with different statistics on building service life. Similarly, the approach adopted in this research relied on those cities where the digitization of geography information system is well established. With the availability of more comprehensive GIS data, this approach could provide more reliable results, and could be used for similar studies in other regions.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.conbuildmat.2016.03.130.

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