The effects of green building on construction waste minimization: triangulating 'big data' with 'thick data'

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Abstract

In contrast with the prolific research examining the effects of green building (GB) on property value, energy saving, or indoor air quality, there has been minimal focus on GB's effects on Construction Waste Minimization (CWM), which is also an important aspect of cultivating sustainability in the built environment. To address this significant knowledge gap, this study has two progressive objectives: (1) to ascertain the empirical effects of GB on CWM and; (2) to identify and understand the causes leading to the ascertained effects. This is achieved by triangulating quantitative 'big data' obtained from government agencies with qualitative 'thick data' derived from case studies and interviews. The study found that BEAM Plus, the latest version of the Building Environmental Assessment Method developed by the Hong Kong Green Building Council (HKGBC), gave rise to a 36.19% waste reduction by weight for demolition works, but no statistically significant waste reduction for foundation or building works. It is because CWM, the basis for a demolition project to obtain GB credits, makes up only one of many ways for foundation or building works to earn credits, e.g., site aspects, lighting. In any case, CWM measures typically prove costlier means of acquiring credit, further causing developers to pay less attention to CWM in their GB tactics. The study's results, i.e., CWM in GB significantly influences demolition, but only marginally for foundation and building works, provide useful scientific evidence to inform GB councils and other responsible bodies and encourage continuous improvement in GB practices. While the study in general sheds light on how the triangulation of big, empirical data with conventional, qualitative data, e.g., interviews with GB professionals, helps to better understand the subject of the

investigation, i.e., the effects of GB on CWM.

Keywords: Construction waste management; Green building; BEAM Plus; Big data; Hong Kong.

Introduction

Buildings house the vast majority of social and economic activity, as well as influence human health and behavior. They also exert serious adverse impacts on the natural environment in the form of resource depletion, greenhouse gas (GHG) emissions, noise, dust, and waste. In the United States alone, buildings account for almost 40% of the country's CO_2 emissions, but LEED-certified buildings have 34 percent lower CO_2 emissions, consume 25 percent less energy and 11 percent less water, and have diverted more than 80 million tons of waste from landfills. Construction work and buildings are responsible for 40% of the consumed raw materials, 40% of the waste deposited in landfills, and 30% of energy-related greenhouse gas emissions (Napier, 2016). The global green building (GB) movement has advanced a myriad of strategies for fostering a better built environment, while alleviating the adverse impacts human development has caused the natural world thus far. A polysemous word, building here both refers to the noun of a physical building and the gerund of building activities. Various green building rating systems (GBRS) define GB standards and award GB certification. Notable ones include Leadership in Energy and Environmental Design (LEED) in the USA, Building Research Establishment Environmental Assessment Method (BREEAM) in the UK, Green Building Label (GBL) in China also known as China Three Star, Building Environmental Assessment Method (BEAM) in Hong Kong, Green Star in Australia and New Zealand, Comprehensive Assessment System for Built Environment Efficiency (CASBEE) in Japan, and Building Construction Authority Green Mark Scheme in Singapore.

GB projects normally incur higher upfront costs than ordinary buildings due to the use of more sustainable, less conventionally marketed materials and Mechanical, electrical, and plumbing (MEP) systems. GB institutions propagate that the higher cost can be paid off in the long run through improved environmental performance and thus lower utilities bills, higher property value and rates of occupancy, and greater levels of occupant comfort and productivity (Kats et al., 2003). A plethora of research exists to support these claims, e.g., Fuerst and McAllister (2011) on GB effects on property market price; Shuai et al. (2018) on carbon emission reduction; Castleton et al. (2010) on energy savings for retrofits; Singh et al. (2010) on employee health and productivity; Zhang and Altan (2011) on occupant comfort. In contrast, research into the effects of GB on Construction Waste Minimization (CWM) appear to be few and far between.

Building generates a significant portion of the world's total solid waste. Statistics show that waste generated by building activities normally constitutes between 20 and 30% of the total solid waste deposited in landfills for most developed economies, such as that of the USA, Europe, Hong Kong and Japan (USEPA, 2016; European Commission, 2013; HKEPD, 2016; MoE, 2014). This rate is even higher for developing countries (Lu et al., 2016b). Landfilling construction waste leads to its anaerobic degradation and CO_2 and methane production, which further results in extensive amounts of air, water and soil pollution (Kightley et al., 1995). It also exhausts valuable landfill space (Lu and Tam, 2013). As worldwide building activity increases, so does the need to assuage construction waste. CWM plays an important role for the building industry in its pursuit of sustainability, reflected in various GBRS. Studies conducted to investigate the scope of GBRS have unanimously deemed CWM pertinent to GB development (Tam et al., 2004; Wu et al., 2016), accounting for 8% to 12% of credits in these systems, particularly in terms of sustainability assessment (Wu et al., 2016). However, there appears to be no studies convincingly utilizing big data approaches to examine whether GB development truly influences CWM.

This study aims to address this knowledge gap by determining the causal effects of GB development on CWM through two progressive objectives. Firstly, to ascertain the effects of GB certification on CWM, the authors assume an inverse relationship between the amount of construction waste sent to landfill and GB rating scores. This hypothesis is tested by making good use of a set of 'big data' derived from various sources to paint of a fuller picture of GB development in relation to CWM. The second objective concerns identifying and understanding the causes resulting in the ascertained effects by triangulating quantitative, big data with qualitative, 'thick data' (Rasmussen and Hansen, 2015) derived from case studies, archival research, focus group meetings, and interviews with GB professionals. This task helps probe into how sustainability deliverables are interpreted by and aligned with developers' GB strategies. For the sake of practicality, the research is contextualized in Hong Kong, where both the GB movement and CWM developed profusely. However, they are not juxtaposed to enable the formation of a holistic view of their dynamics. In order to provide an understanding of the inherent link between GB and CWM, Section 2 offers a review of building-related construction waste and GB movement literature, followed by an account of the research methodological approach in Section 3, an analysis of the data in Section 4, and a discussion of the results in Section 5. Conclusions are drawn in the final segment of the paper.

2. Literature review

2.1 Building-related construction waste

'Construction waste', often used interchangeably with 'construction and demolition (C&D) waste', concerns the surplus or damaged materials that result from building activities, such as new construction, renovation, and demolition (Roche and Hegarty, 2006). The composition of construction waste largely depends on the prevailing construction materials and technologies available to that construction project. The European Waste Catalogue (EWC) classifies C&D waste into eight categories, i.e., concrete, bricks, tiles and ceramics; wood, glass and plastic; bituminous mixtures; metals; soil; insulation; gypsum-based construction material; and everything else. In the UK and commonwealth countries, C&D waste often falls into either inert or non-inert categories. The former comprises soft inert materials such as soil, earth, silt, and slurry, as well as hard inert materials such as asphalt, rocks and broken concrete. Non-inert C&D waste normally include timber, bamboo, vegetation and other organic materials, glass, plastics and other packaging waste (Wu et al., 2014; HKEPD, 2013). Unlike inert materials, non-inert ones cannot be easily reused or recycled and thus have to be landfilled. Landfill non-inert waste will quickly consume landfills, which are often the valuable assets of a city.

C&D waste often constitutes a significant volume of the world's total solid waste. In the USA, for example, the estimated amount of C&D waste generated in 2014 before recycling was 534 million tons, over twice as much as the 258 million tons of municipal solid waste (MSW) recorded that same year (USEPA, 2016). The European Commission (2013) estimated construction waste comprised 25-30% of all the waste generated in the European Union. Lu et al. (2016b) calculated that China produced approximately 1.13 billion tons of C&D materials in 2014, about 30-40% of its total annual solid waste. HKEPD (2016) reported that the solid waste dumped in Hong Kong landfills reached 15,332 tons per day in 2016, 29% of which came from construction activities. Likewise, in Japan, construction contributes to 20% of all industries' total solid waste (MoE, 2014).

C&D waste is not entirely synonymous with environmental pollution and resource depletion. Successful examples of construction waste reuse and recycling abound, e.g., Park and Tucker (2017). A large proportion of waste, such as metals, rocks, and broken concrete, can be reused as architectural or material salvage or recycled as Portland cement clinker, artificial aggregates, road pavement, or reprocessed bricks. Nevertheless, a certain portion of C&D waste, the non-inert compositions in particular, cannot be reused or recycled, and therefore must be landfilled. Landfilling waste leads to considerable pollution to air (Sam-Cwan et al., 2001), water (Mor et al., 2006), and soil (Garcıa-Gil et al., 2000). It also exerts tremendous pressure on valuable landfill space, particularly in compact urban spaces (Lu and Tam, 2013). As a concomitant by-product of building, construction waste must be properly managed (Teo and Loosemore, 2001).

CWM strategies can be understood through the "3Rs" principle, denoting reduce, reuse, recycle strategies, which are pursued according to their desirability given the situation (Wu et al., 2013; Peng et al., 1997). 'Hard' and 'soft' approaches characterize two common types of construction waste management. Environmental engineers have investigated how hard technologies can help reduce, reuse or recycle C&D waste through the introduction of prefabrication (Tam et al., 2005), the manufacture of recycled aggregates for various concrete applications (Rao et al., 2007), and site formation or land reclamation (HKEPD, 2013). Recognizing that waste constitutes a social issue, soft economical or managerial measures embrace implementing a waste disposal levy and mandating waste management plans (HKEPD, 2015), advocating 'design out' waste schemes (Baldwin et al., 2007; Osmani et al., 2008), or promoting onsite waste management (Wu et al., 2017; Shen et al., 2004).

2.2 The green building (GB) movement

Buildings are typically designed and constructed to meet building code requirements, whereas GB solicits design beyond the obligatory in order to enhance overall building performance and minimize lifecycle environmental impacts and cost (Gowri, 2004). Robichaud and Anantatmula (2010) describe the four pillars of GB as the reduction of environmental impacts, enhancement of the occupant health conditions, return on investment for all stakeholders, e.g., developers, local community, and lifecycle considerations during the planning and development process. Various Green Building Rating Systems (GBRS) evaluate and administer GB credentials largely on a voluntary yet market-based premise. Stacks of research have covered these schemes, e.g., Cole (2003), Wu and Low (2010), and Wu et al. (2016), although they differ in terminology, assessment methods, weighting of environmental themes, and documentation requirements for certification. Nevertheless, they share a certain degree of similarity, having similar roots and themes, such as energy efficiency, water conservation, site selection, building materials, and indoor environmental quality, among others. Based on the GBRS, normally a third-party GB accreditation body measures the total 'green' points of a building and awards a certification label recognizing the building's green credentials.

The widely propagated benefits of GB from the environmental perspective include biodiversity enrichment, protection of the ecosystem (Bianchini and Hewage, 2012), and reduction of greenhouse gas emissions (Shuai et al., 2017). Meanwhile, GB also brings social benefits, such as improved health conditions, occupants comfort (Zhang and Altan, 2011), social productivity (Singh et al., 2010), aesthetic appeal, and CWM (Wu et al., 2016). Numerous studies have investigated whether GB truly achieves these benefits with largely affirmative results, e.g. Newsham et al. (2009); Menassa et al. (2011), despite some conflicting findings, e.g., Scofield (2009). Likewise, McAllister reviewed a horde of studies examining GB's effect on property prices in 2012. In contrast, few studies on GB's impact on CWM exist.

Most GBRS accept CWM as a GB indicator and credit. Wu et al. (2016) compared five GBRS by focusing on how they encourage CWM and identified the relative significance indexes of CWM. Essentially, the related initiatives to CWM that can be obtained from the GBRS are: 10% according to LEED, 8.16% for BREEAM, 11.5% for Green Globes, 11.84% for Evaluation Standard for Green Building, and 8% for Green Building Index. Allowing CWM efforts to account for about 10% of all points awarded in a GBRS without concrete evidence of their effects not only constitutes a significant knowledge void, but also problems for promoting GB development. Any small adjustment to the GBRS carries enormous material implications for stakeholders, which include investors, owners, designers, consultants, and contractors.

3. Research Methods

This study examines whether GB definitively has a positive effect on CWM or not. As mentioned previously, there are two progressive objectives to be achieved, i.e., to ascertain the effects of GB on CWM by hypothesizing the relationship between the amount of construction waste sent to landfill and GB rating scores, and to identify and understand the causes leading to the ascertained effects. By triangulating quantitative, 'big data' with qualitative, 'thick data' the value of any effect becomes evident.

3.1 Context

For practical reasons, this research is contextualized in Hong Kong, which the World Green Building Council (WGBC) (2015) has praised as a leader in the GB movement. BEAM is the dominant GBRS in Hong Kong, followed by the LEED (WGBC, 2015). As of 20 June 2016, 808 projects in Hong Kong were registered for the BEAM Plus certification (HKGBC, 2016), consequently this study uses BEAM Plus for New Buildings, referred to as "BEAM Plus" within this article, to test the above hypothesis. Established in 1996, BEAM is largely based on the UK BREEAM (Prior, 1993). After several reiterations, the current version of BEAM Plus was formally released in November 2012. It includes six aspects of a building: Site; Energy Use; Indoor Environmental Quality; Materials; Water Use; and Innovations and Additions. CWM measures fall under Materials Aspects (see Table 1). The overall attainable grade awarded to CWM-related initiatives calculate according to the approach provided by HKGBC (2012). First, BEAM Plus identifies waste-related items as listed in Table 1. Material Aspects received 22 credits in total, which only equates to 8% of the overall grade. Then, the attainable credits and bonus credits combine, presenting the overall grade for each item in the fifth column of Table 1 using the equation $\frac{Attainable\ credits\ and\ bonus}{\text{Category credits in total}} \times 8\%$. The highest attainable grade overall for waste-related items accounts for 5.09% of the total BEAM Plus score, hence the percentage for BEAM Plus is slightly less than that of international practice as reflected in other GBRS.

Table 1 Weighting of the items aiming for CWM in the BEAM Plus (HKGBC, 2012)

Items		Attainable credits	Attainable bonus	Attainable overall grade
Material Aspects (MA) (weighting 8% of overall grade; totally 22 credits)				
MA P_1	Timber Used for Temporary Works	Required		
MA P_3	Construction/Demolition Waste Management Plan	Required		
MA P_4	Waste Recycle Facilities	Required		
MA_1	Building Reuse	2	1	1.09%
MA_2	Modular and Standardized Design	1		0.36%
MA_3	Prefabrication	2		0.73%
MA_4	Adaptability and Deconstruction	3		1.09%
MA_6	Sustainable Forest Products	1		0.36%
MA_{10}	Demolition Waste Reduction	2		0.73%
MA_{11}	Construction Waste Reduction	2		0.73%

The scant attentions to the effects of GB on CWM attributes to a lack of quality data in relation to both GB and CWM. In real-life practice, contractors do not have to record waste data onsite.

Data collection thus occurs sporadically if at all. When a building project completes, it ceases to generate construction waste, and the opportunity to collect waste data expires. Previous CWM studies typically adopt data collection methods like direct observation (Poon et al., 2001); questionnaire surveys (McGregor et al. 1993); sorting and weighing of waste materials on-site (Bossink and Brouwers1996); tape measurements of volume and truck load records (Skoyles 1976; Poon et al. 2004); and collecting data through consultation with construction company employees (Treloar et al. 2003). Obtaining good data on GB can prove equally difficult, if not more so. The ideal situation would be to obtain GB profiles, e.g., developer, gross floor area (GFA), contract sum, construction technologies, and GB label (GBL) data from a single source, such as a green building council (GBC) or other body responsible for instituting GBRS. However, these bodies do not normally circulate this data as they contain client information and commercial secrets, which limits the amount of sample sites for study (Lu et al. 2011), and such studies' ability to account for the totality of waste generation throughout the building process (Katz and Baum 2011).

Nevertheless, this research has managed to collect rich data relating to CWM and GB in Hong Kong. The special administrative region enjoys a robust building sector. Contractors are mandated to dispose of their waste at government facilities, specifically landfills or public fills, if not otherwise properly reused or recycled. The Hong Kong Environmental Protection Department (HKEPD) records every truck of construction waste received at these facilities, logging around 3,300 records per day. Profiles document the waste's site address, client, and project type. This study secured all the data from 1 January 2011 to 30 June 2016, which contained 7,045,539 disposal records generated from all construction works in Hong Kong, 26,566 sites in total (see Fig. 1). Although the datasets emerged from various databases, all were well structured, and provided complete and reliable data for probing into CWM. This study has also sourced the data of all the 808 buildings (as of 20 June 2016) certified or registered for certification as BEAM Plus. The information pertaining to the 808 buildings, including project names, site addresses, level of GB label, and their waste generation records, forms the big data set as shown in Fig. 1.

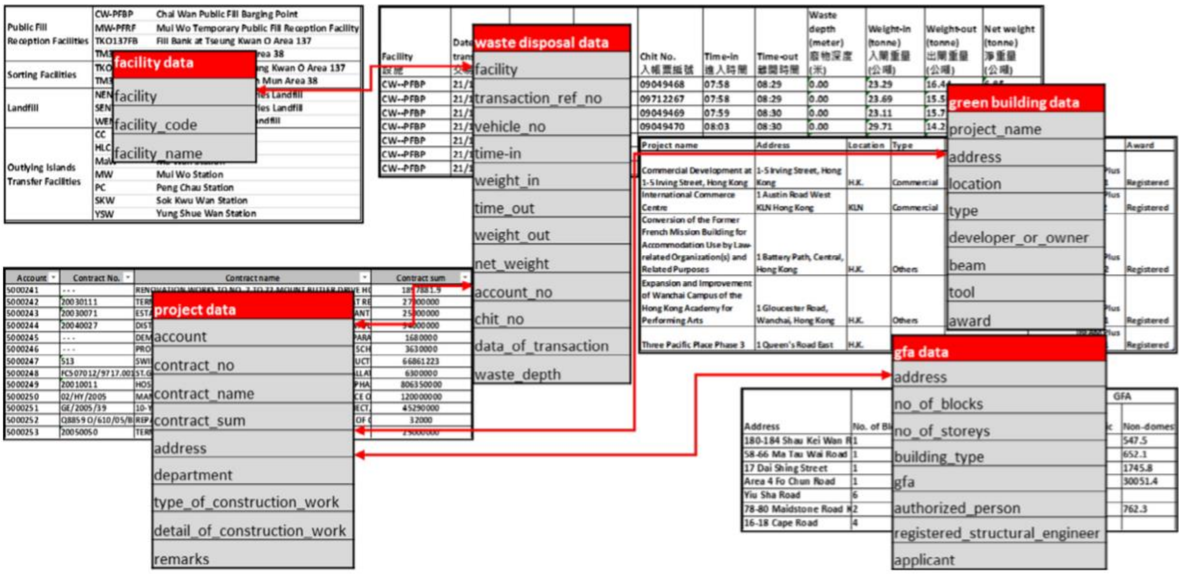

Fig. 1. The big data set used in this study.

3.2 Modelling the effects of GB on CWM

A building developer, through its hired professionals, incorporate green features in part to obtain credits as designated by GBRS. It therefore stands to reason that high-performance GB should likely reflect best practice in CWM compared to business-as-usual projects. It is hypothesized that:

> *H: All other things being equal, achieving a higher level of green building label will contribute positively to waste minimization, i.e., lead to a lower level of waste generation.*

Dependent variable – Waste generation rate (WGR).

The WGR has been widely used to measure waste generation in a building project. A WGR can be calculated by dividing the waste in volume (m^3) or quantity (tons) by either the amount of virgin materials purchased, the amount required by the design, or per m^2 of gross floor area (GFA) of the finished building (Formoso et al., 2002). Actually, the two measures using volume and quantity are interchangeable with one another based on a rule-of-thumb formula. Studies, such as Lu et al. (2015) and Lu et al. (2016a), employed contract sums (CSs) to replace GFA in calculating WGR, since all projects have clear construction sums, but not necessarily GFA. CSs indicate the wastage rate of producing every certain amount of construction works. Following this argument, the WGR of building i is defined as: $WGR_i=WG_i/CS_i$ where i is the project number, WG_i is the waste generation quantity, and CS_i is the contract sum.

Independent variable - green building label (GBL).

GBL levels can be placed in a set using mathematical language: *GBLi = {Unclassified, Bronze, Silver, Gold, Platinum}*. A natural solution is to allocate discrete scores to the options in statistical analyses, i.e., assign a 0 to Unclassified, a 1 to Bronze and so on. However, owing to improved data availability, the hypothesis can be expressed as: $GBLi\uparrow \rightarrow WGRi\downarrow$.

Control variables

As previously discussed, the WGR is affected not only by a building's GBL, but also by other confounding factors, which form the control variables in the analyses. Previous studies have touched upon various factors impacting building waste generation, including building type, e.g., commercial or residential (BRE, 2009; Akotia and Sackey, 2017); building technology, e.g., cast in-situ or prefabrication (Tam et al., 2005); contract sum; duration (Chen and Lu, 2017); and building GFA (Poon et al., 2004). Among the above factors, applied building technologies in the construction industry make little difference between 'green' and 'ordinary' buildings in a certain period of time. In addition, contract sum is used as a proxy of GFA (Lu et al., 2015) to measure WGR, signifying the high correlation between the two factors. It was found that contract sum and project duration correlate (Chen and Lu, 2017). Since they both have strong relationship with contract sum, the use of contract sum as the denominator in calculating WGR in this study has considered the effects of GFA and project duration have been considered in the statistical analyses.

3.2 Testing the hypothesis

Various statistical methods can be applied to test the hypothesis concerning the relationship between GB and CWM, i.e., the GBL and the WGR. One typical concern for using a statistical method is the number of observations, e.g. sample size and data volume, needed to reach the desired precision. Regression model, ANOVA, or non-parametric methods can become data greedy when there are several independent variables and confounders which have to be controlled (Elwakil, 2017). By using the big volume of data, it is anticipated that the large population of samples can mitigate the effects of the control variables to isolate the effects between GB and CWM performance.

The selection of appropriate statistical methods presents another concern. Previous studies have established that the WGRs for overall construction works in Hong Kong follow a positively skewed distribution, and therefore median instead of mean is used to present the WGR value, i.e., the waste management performance, e.g., Lu et al., 2015; Lu et al., 2016a. If this is the case in our study, the median WGR rather than the mean WGR would be a better representative of the CWM performance. The significance of difference in distinct building types can be statistically examined using Mood's median test approach, a nonparametric test that assesses the equality of medians from two or more populations.

3.3 Triangulating the 'big data' with the 'thick data'

Triangulation of the big data with thick data helped identify and understand the causation of the nexus between GB and CWM. This study sourced ten BEAM Plus certified buildings (to be seen in Table 5 later) as case studies, which allowed the exploration and perception of complex issues based on primary data. This constitutes a robust research method, particularly when attempting a holistic, in-depth investigation. This study examined the ten buildings, along with their profiles, stakeholders, and most importantly, the detailed GB scores that led them to a certain green building label. Based on the empirical analyses and the case studies, this study conducted eight semi-structured interviews with GB professionals, contractors and recyclers, between July 2017 and November 2017 (See Table 2). The interviews were not transcribed fully but the main points were put in a spreadsheet. Triangulating the 'big' and 'thick' data has enabled this article's authors to tease out more convincing narrative evidence of GB's effects on CWM.

Table 2 Profile of the interviewees

No.	Role	Working experience
1	Past President of HKGBC	>30 years
2	GB expert in a university, architect	>15 years
3	HKGBC Council Member	>20 years
4	Inspector of a government waste facility	>16 years
5	GB consultant in a world leading consultancy firm, architect	>20 years
6	Director of a recycling firm	> 10 years
7	GB assessor	>15 years
8	Manager of a real estate development firm	>18 years

4. Data analyses and results

4.1 Computing WGRs of 'green' and 'ordinary' construction works

A building project normally consists of three main consecutive stages, i.e., demolition of the old structure, foundation work, and building of the new structure. In prevailing practice, a project contracts out as multiple work packages to different contractors. It is also common for the developer to apply for Hong Kong BEAM Plus, LEED, or both certifications through one or more such packages, e.g., applying for GB label for its demolition, applying separately for building works. With Hong Kong BEAM Plus, a prospective developer hires a GB advisor to register the building first, then work with the GB assessor throughout the building process. One may notice that some of the Hong Kong BEAM Plus certificates are 'provisional' while others are 'final'. To avoid ambiguity, construction works earn the title of 'green', while business-as-usual works that of 'ordinary'. Due to the wealth of data, this study was able to compare green works with ordinary works at different stages, namely demolition, foundation and building. Such separate analyses provided greater insight into the effects of GB on CWM.

For each work, the amount by weight of every lorry load of C&D waste was extracted from the 'waste disposal' database. With the use of contract sum, the WGRs of GB demolition, foundation, and building works were calculated using Equation (1). For a construction work i, which sent j truckloads of construction waste to the government waste disposal facilities, the WGR for project i can be expressed as:

$$WGR_i=(WG_{i1}+ WG_{i2}+ WG_{i3}+\ldots\ldots +WG_{ij})/CS_i \qquad (1)$$

Where the sum of WG_{ij} represents the waste generation of construction work i and CS_i is the contract sum of work i. In Hong Kong, construction waste falls into one of two categories, i.e., inert and non-inert construction waste, which could be generated at any stage of a project, i.e., demolition, foundation, or building works. The WGR formula is thus applied to computing six groups of WGRs, i.e., inert construction and non-inert construction waste for each type of construction work.

4.2 Comparing the WGRs between green and ordinary construction works

Following the above rationale to examine CWM for individual building stages, i.e., demolition, foundation, and building, the overarching hypothesis *H* can be further developed:

> H_1: *All other things being equal, achieving a higher level of green building label (GBL) will contribute positively to waste minimization, i.e., lead to a smaller WGR, at the demolition stage; and*
>
> H_2: *All other things being equal, achieving a higher level of green building label (GBL) will contribute positively to waste minimization, i.e., lead to a smaller WGR, at the foundation stage; and*
>
> H_3: *All other things being equal, achieving a higher level of green building label (GBL) will contribute positively to waste minimization, i.e., lead to a smaller WGR, at the building stage.*

This study regulates the periods for qualified samples should fall in the range from 1 February 2011 to 20 May 2016. This is for the purpose of to the largest extent making sure all the samples having waste disposal records that could be provided by the collected data of this study. If a project barely had waste generation in either first month (1 to 31 January 2011) or in the last month (the period from 20 May to 20 June 2016), the project is probably started and completed in the period from 1 January 2011 to 20 June 2016 as they seldom generate waste in the first and last months. Reversely, if a construction work generates waste in either one of the two months, it probably had started before 2011, or had not ended yet before 20 June 2016. Then a confidence level of 95% is added to exclude outliers to enable the six groups of WGRs to have more credibility. The profile of qualified construction works are shown in Table 3. The WGRs of green and ordinary construction works at demolition, foundation, and building stages are plotted in Figs. 2, 3, and 4, respectively. In Figs. 2, 3, and 4, the value on the y-axis means the WGR of a single construction work measured in ton/mHK$. The value on the x-axis stands for the serial number randomly assigned to an individual construction work for the convenience of the data analysis. For example, the x1 in Fig. 2 ranges from No. 1 to 157, standing for the 157 green demolition projects; and the x2 in Fig. 2 is from No. 1 to 205, standing for the 205 ordinary demolition projects without attempting to achieve a BEAM Plus label.

Table 3 Profiles of the number of each type of the construction works

Construction type	No. of green works	No. of ordinary works
Demolition	157	205
Foundation	238	276
Building	61	200
Total	456	681

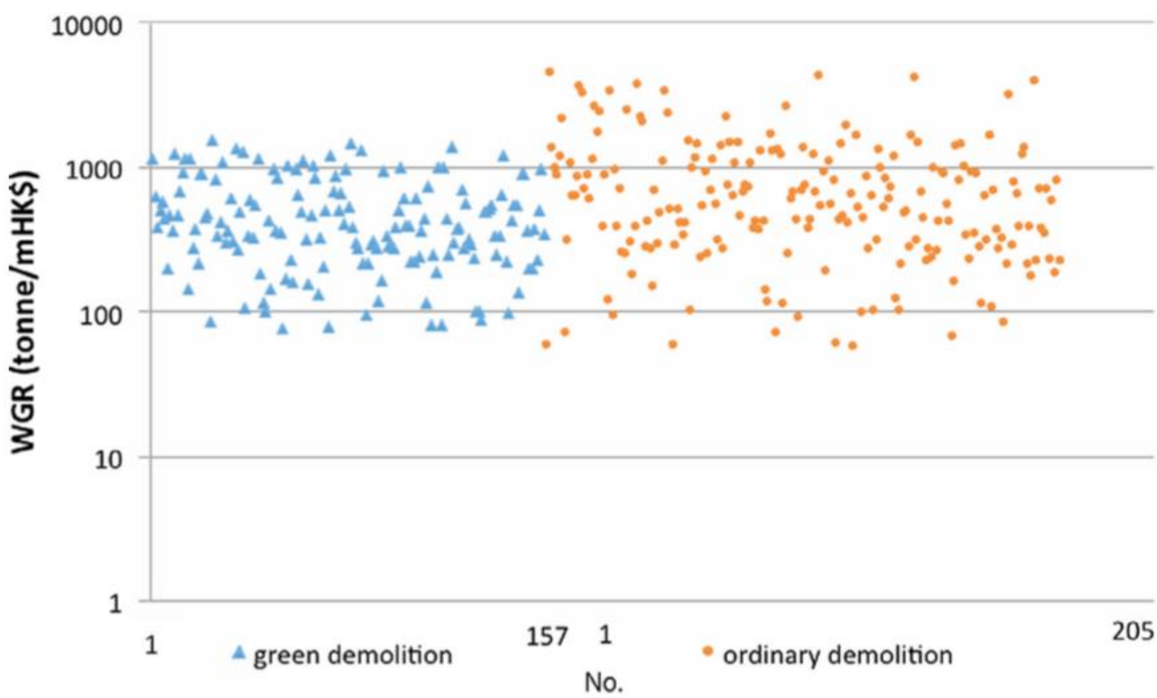

Fig. 2. Green and ordinary demolition works compared.

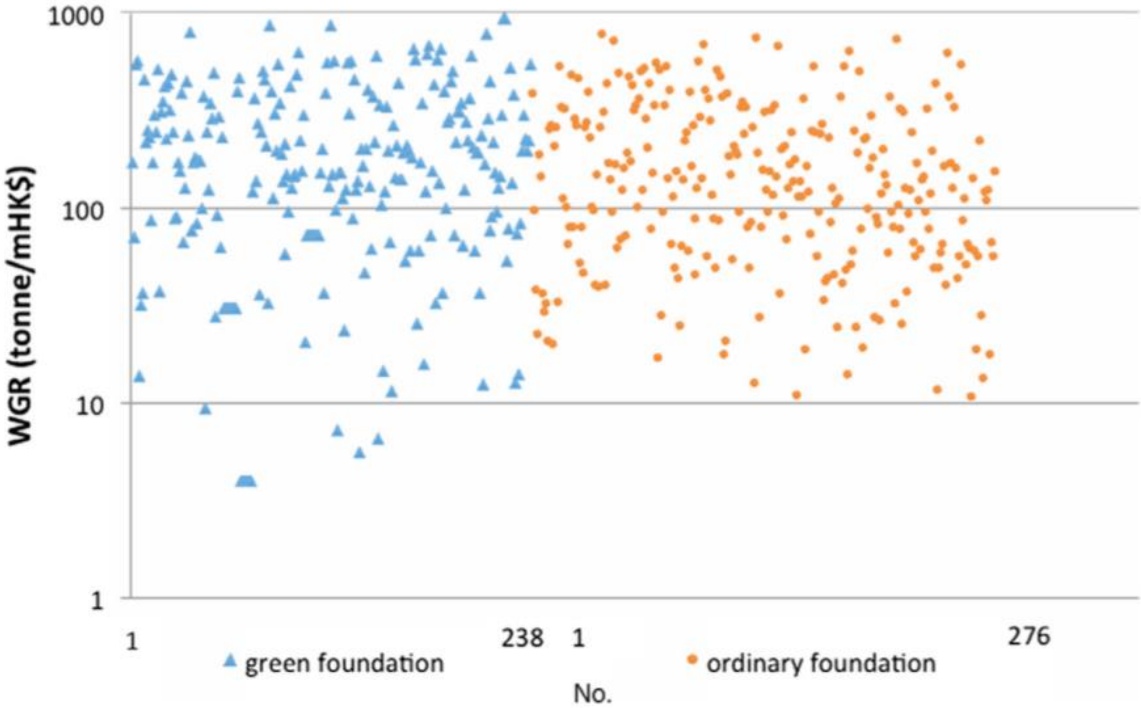

Fig. 3. Green and ordinary foundation works compared.

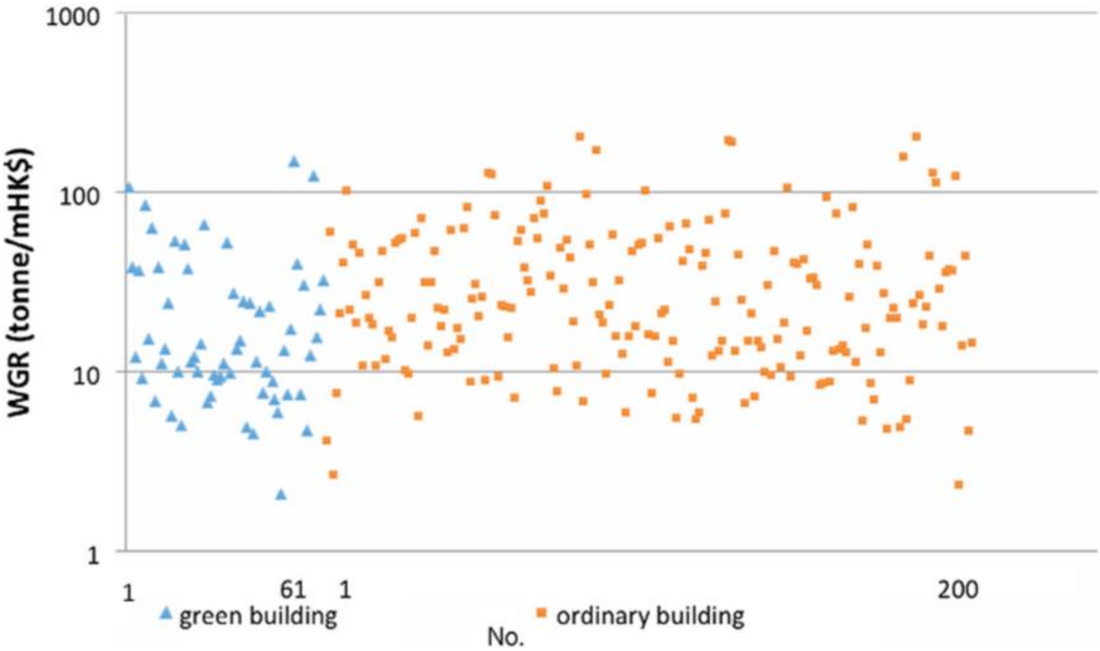

Fig. 4. Green and ordinary building works compared.

There is no clear trend of the WGR distributions in Figs. 2, 3, and 4 but after plotting the histograms of the identified groups, all the groups tend to follow a positively skewed distribution (see Fig. 5). This resonates with previous studies, e.g., Lu et al., 2015 and Lu et al., 2016a, which discovered a positively skewed distribution of WGRs. The means and medians are calculated and listed in Table 4. With other confounders controlled, if a green project has lower WGR than an ordinary project, this project can be regarded as stimulated for improving CWM performance by the BEAM Plus due to its attempts to gain the GB credits. The difference between green and ordinary medians for each construction type is calculated and listed in the seventh column of Table 4, which equals the value of the second column minus the value of the fourth column. The significance of the difference is statistically examined using Mood's median test approach owing to its appropriateness. The test is conducted in *R*, an open-source software for statistical computing and graphics. The table also lists the *p*-values of the test and the significances of the differences of median WGRs between green and ordinary groups. When *p*-value is less than 0.05, the difference between the medians can be regarded as 'significant'. A positive value of the WGR difference with a 'Yes' difference significance indicates the BEAM Plus negatively affects waste minimization for that type of construction works, while a negative value with a 'Yes' stands for a positive impact. Otherwise there is no significant evidence that the BEAM Plus influences CWM. Table 4 shows that only the demolition works are significantly affected by the BEAM Plus in terms of the WGR difference (WGR difference=-219.18 tons/mHKD, and WGR significance=Yes), while other construction types, i.e., foundation and building, remain unaffected according to the "No"s. Therefore, H_1 is supported. It can be considered BEAM Plus played positively on the CWM for demolition works. However, the p-values for examining the significances of differences of foundation and building works between the green and ordinary types are larger than 0.05. H_2 and H_3 are not supported. The results indicate that BEAM Plus has not yet obviously differentiated green buildings from ordinary buildings on their foundation and building works in its CWM performance. The significant amount of samples fail to demonstrate the advantage of CWM performance when applying BEAM Plus. It would therefore appear that this GBRS could not effectively incentivize the CWM aspect as part of its general aim of pursuing sustainable development.

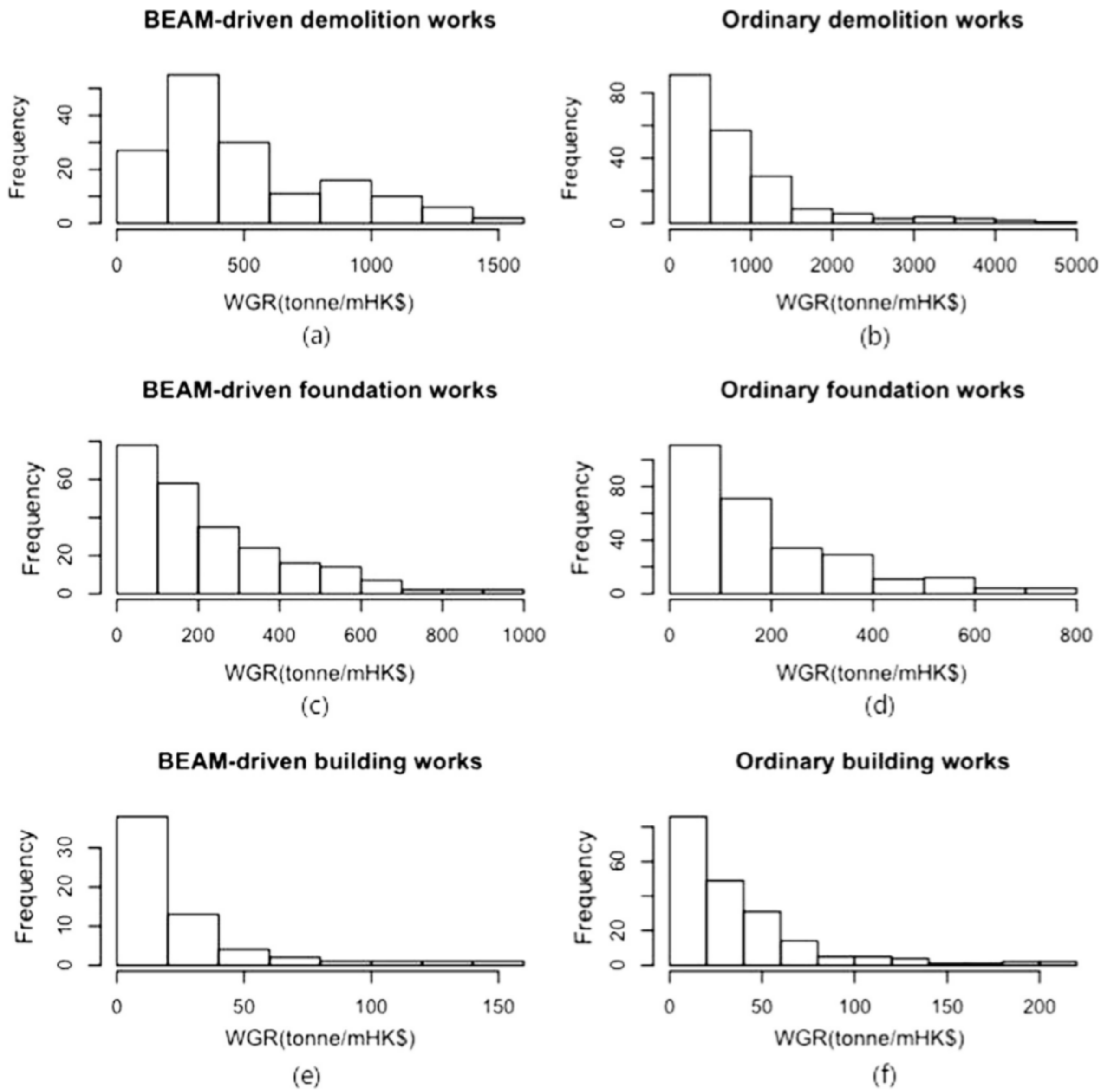

Fig. 5. Histograms of WGRs of green and ordinary construction works.

Table 4 Mood's median test results: Green and ordinary construction works compared

Construction type	WGR of green projects (ton/mHKD)		WGR of ordinary projects (ton/mHKD)		*p*-value (Mood's Median test)	Median WGR difference (ton/mHKD)	Percentage of waste reduction	Existing significant difference?
	Mean	Median	Mean	Median				
Demolition	502.13	386.47	869.07	605.65	0.004	-219.18	+36.19 %	Yes

Foundation	226.75	170.65	186.77	127.54	0.066	43.11	-33.8%	No
Building	25.49	13.25	37.41	22.99	0.288	-9.74	-42.37%	No

4.3 The effects of GB on CWM explained

The most valuable finding of this study is that the BEAM Plus for Existing building leads to better CWM performance only for demolition works, yet in statistical terms has barely any influence on foundation and building works. It has been widely accepted that demolition works generate a large amount of waste, without managing what the whole building can turn into waste (Chen and Lu, 2017). Therefore, efforts of demolition waste management have been stipulated in the design of a GBRS (see Table 1). For example, for some old buildings to be demolished, the structures are still healthy, reuse of which is given high credits (referring to MA_1, which is categorized in Material Aspects [MA] in Table 1). One of the interviewees particularly mentioned a public housing demolition project in Hong Kong:

"This project is a traditional precast building, to demolish which is becoming difficult owing to the loss of design information decades ago. Therefore, they even developed a building information model (BIM) to demonstrate how the demolition work can be done sequentially and safely. The client [The Hong Kong Housing Authority] has decided to make this an exemplar project from the outset, so they applied for BEAM Plus Certification. They tried their best to reuse or recycle the waste materials in other government projects. They have time to tolerate".

In addition, MA_4, which involves deconstruction, a type of demolition measures, and MA_{10}, which directly emphasizes demolition waste reduction, are both considered as items mainly relating to demolition waste reduction. The total weighting of MA_1, MA_4, and MA_{10} accounts for 4.05% of overall attainable credits, while that aiming for waste reduction at foundation and building stages is only 1.05%. In addition, it is clearly more practical to recycle and reuse demolition waste, which generates in large quantities within a short period, while it is less operative to reduce waste generated at foundation and building stages with less possibility of reusing it over a longer period. This has been echoed by an interviewee:

> *"Timing is extremely critical for reuse or recycling of construction waste, particularly in Hong Kong where everything is running fast. You can have a plan to use it in other government projects when you know there is a steady stream of supply [of waste]. Yet, this would not happen when there is no other construction works coincidently demands such waste, e.g. for backfilling".*

After all, dealing with the generated waste in a safe and green manner is the major responsibility of demolition work, and through it, one can obtain BEAM Plus credits while for foundation or new building works, developers have other ways of doing so which are arguably less complicated. The insignificant influence of GB on CWM can also be explained by the unit cost disparity in obtaining a credit from different aspects included in the BEAM Plus. Table 5 shows the detailed credit distributions of projects that have been showcased as green buildings in Hong Kong. CWM is included in MA category. It can be seen from Table 5 that interestingly developers consistently scored low in MA.

Table 5 Details and total scores of green buildings evaluated by using the BEAM Plus

Name	Certification	SA (%)	WU (%)	IEQ (%)	EU (%)	MA (%)	I&A	Total Score	Completion Year	Type
A	Provisional Platinum	71	88	90	75	56	6	83.1	2016	Commercial
B	Final Platinum	76	57	89	85	72	6	85.5	2016	Government, Institutional and Community
C	Provisional Platinum	76	71	84	76	50	5	80	2013	Mixed Use

D	Provisional Platinum	81	38	89	92	33	5	82.3	2017	Government, Institutional and Community
E	Final Platinum	70	63	74	75	72	6	77.9	2012	Government, Institutional and Community
F	Provisional Platinum	79	75	100	95	40	6	90.9	2018	Government, Institutional and Community
G	Final Gold	60	63	87	68	41	3	70.1	2014	Residential
H	Final Platinum	74	75	79	84	30	5	79.8	2012	Hotel
I	Provisional Platinum	86	71	89	83	44	6	86.7	2013	Government, Institutional and Community
J	Provisional Platinum	86	78	81	94	33	6	88.7	2018	Government, Institutional and Community

SA= Site aspect; WU=Water use; IEQ= Indoor environmental quality; EU=Energy use; MA= Materials Aspects; I&A=Innovations and Additions

An interviewee who is a GB council member reflected:

> *"They [architects working for the developers] will not tell you their tricks. That is their expertise to make a living".*

But, more than one architect was actually willing to share their views on condition of anonymity:

> *"Using new and green materials is not necessarily more expensive. The issue is the supply and the logistics arrangement. Whether the suppliers are familiar with them and guarantee a stable supply. By considering these, to gain a point from MA is thus not easy and it could be very expensive."*

This echoes with the above interviewee who mentioned the importance of timing. Actually, Hong Kong charges contractors for disposal of construction waste. A developer can 'double-dip' when it comes to minimizing C&D waste both by saving the waste charging levy imposed by the EPD and obtaining the GB credits from the GBC. Yet, they are reluctant to do so owing to the effort required of planning and conducting CWM. The saving is almost negligible if comparing with the high housing price and the labor cost to manage the waste. Another interviewee added separately:

> *"You can easily get some credits by doing something such as rooftop planting, water efficient irrigation, you know, that kind of stuff. It is our company's policy that we led our visitors to the rooftop as the first step of any site tour".*

Although, it was not possible to ask the architects of the above ten case projects to interpret their GB tactics, based on the above quantitative and qualitative data analyses, it is reasonable to assume that since obtaining a GB credit from CWM constitutes a costlier measure, one can assume developers normally play down CWM.

5. Discussion

5.1 Too simplified to recommend a more delicate design of GBRS

The research findings of this study proved intriguing, yet surprising. Challenging the orthodox wisdom that BEAM Plus, as a form of GB public policy with a certain scope focusing on CWM, achieves its desired effect, the temptation is to make a series of recommendations to further fine-tune the GBRS. For example, the attainable credits and bonus for MA11 (Construction Waste Reduction) should be gradually increased until projects feel incentivized to prevent waste accrued during the foundation and demolition stages from landing in disposal facilities. The foundation work, exposed as the most wasteful construction stage, generates the largest amount of excess and damaged material. As such, GBRS should give it greater importance and more potential CWM credits. Although, being the single investigation of its kind, this research may be too preliminary and simplified to make such recommendations.

Pushing for waste reduction at the foundation stage through more attainable credits and bonuses may induce practitioners to shift their attention from demolition and building waste reduction or resolve not to meet these items due to a lower or negligible grade. The evolution of such GB public policies involves imitation, localization, and a manifold of social factors, such as politics, vested interests, compromises, irrationality, even fierce protests. Therefore, this research does not recommend the HKGBC simply modify its BEAM Plus as suggested above. Nevertheless, the research findings from this study provide a scientific knowledge for building evidence, strategies, as well as policy changes and implementation. The surprising findings on the impact of BEAM Plus on construction waste reduction in Hong Kong may motivate global green building legislators to consider the effectiveness of their GBRS with respect to CWM.

5.2 Strengths and weaknesses of big data

Although not as big as a terabyte or petabyte, the empirical data used in this study still constitutes 'big data', based on the criterion that defines big data as that which can account for the totality of the subject under investigation (Lu et al., 2017), and allows values to be created that could not be arrived at with data on a smaller scale (Schönberger and Cukier, 2013). In comparison with the data collected by traditional approaches, certainly this data offers nearly full coverage of all the green buildings in Hong Kong and their waste generation. Without such big data analytics, many insights, e.g., WGRs following a positively skewed distribution, could not be determined, which forces one to misleadingly use mean and other normal distribution methods to examine the subject. The statistical analysis results based on the big data can thus be accepted with a high level of confidence.

Nevertheless, the big data sourced is still too small when it comes to measuring a specific subject, e.g., the 61 green superstructures and the computed WGRs are still manifestly too divergent. This echoes Lu et al.'s (2017) argument of the relativeness of big data. Big data is user relative. A dataset treated as big data to describe one subject may be considered 'small' to another depending on its intended use. Big data does not necessarily always mean better data (Taylor and Schroeder, 2015). Data cleansing helps detect and correct incomplete, incorrect, inaccurate or irrelevant parts of the raw data and allows users to perceive a dataset's true size, value, and relevance to a particular research inquiry.

This research also encourages critical thinking of the integration of big data analytics and traditional ethnographic methods. According to Rasmussen and Hansen,

> "Big data has the advantage of being largely unassailable because it is generated by the entire customer population rather than a smaller sample size. But it can only quantify human behavior, it cannot explain its motivations. That is to say, it cannot arrive at a 'why.' ...While 'thick data' generated by ethnographers, anthropologists, and others adept at observing human behavior and its underlying motivations". (2015).

This paper shows that indeed big data analytics permits the discovery of whether or not GB has an influence on CWM, while triangulating it with thick data can help understand the rationales, i.e., the 'why' behind the ascertained relationship. Criticism that big data has been overhyped is on the rise. This research shows that ethnographic work holds enormous value in the big data era.

5.3 Limitations of the research findings

This study is certainly not free from limitations. The findings cannot be generalized to apply to other economies, as only the Hong Kong context was investigated. Increasingly waste management programs emphasize specific contexts to make them truly operable and effective. However, the research findings still afford various stakeholders with evidence-based reasoning for minimizing waste and useful references in the pursuit of other environmental goals through the GB movement. For future related studies, it is suggested to empirically examine whether other GBRS, e.g., the LEED, have an influence on CWM by using regional big data rather than analyzing the contents of GBRS or GB cases. Although all the available CWM big data was used to present the fullest possible picture of CWM in green building, the number of relevant projects should increase to allow for a more valid analysis.

Conclusion

This study analyzed the effects of green building (GB) on construction waste minimization (CWM) performance by using the dominant GB accrediting system in Hong Kong, the BEAM Plus, as an example. Surprisingly, the results show that the Hong Kong BEAM Plus led to 36.19% waste reduction in demolition projects, the reason being that the demolition waste reduction items grant more GB credits and are more operable than other CWM-related items in the system. However, waste reduction has rarely been stimulated in foundation and building works. In fact, in some projects, waste generation has increased, probably owing to insufficient attainable credits and higher relative costs in order to achieve it. The implication is that CWM-related items of BEAM Plus, particularly relating to foundation and building projects, can be skewed by more credits. Given the proof that most inert waste is generated during the foundation stage, the authors recommend BEAM Plus institute more attainable credits and bonuses for ‘3R’ measures during foundation work.

To the best of the authors’ knowledge, this paper is among the first attempts of its kind. Regardless of the plethora of research relating to the real effects of GB on sustainability performances or property market price, applying big and thick data to understand GB and CWM has yet to be notably or credibly performed. The availability of a big dataset relating to CWM and GB in Hong Kong added to the rigor of this research. The big data applied to traditional applied statistics enabled the effects to be isolated and accepted with a high degree of confidence. Triangulating the data with qualitative case studies and interview data helped achieve a deeper understanding of why such outcomes derive in real practice. Both GB and CWM are emerging global industries. A slight improvement in CWM through the GB movement represents a potential surge in construction and waste transport cost savings, in addition to huge social and environmental benefits. The authors indorse the replication of this research methodology in other economies/GBRS once such data becomes available. This paper thus provides a useful reference for similar research in other contexts to promote GB and CWM.

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